

RESEARCH REPORT



ANIMAL WELFARE

- Title:** Development of improved trailer designs and transport management practices that create the optimum environment for market weight pigs during transport and minimize transport losses – NPB #05-192
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Industry Summary:

The micro-environment experienced by pigs on the trailer during transport is critical for animal well-being and, potentially, impacts transport losses and, ultimately, pork quality. Environmental conditions on trailers during transport have not been previously established, largely reflecting the difficulty of measuring the appropriate parameters during transportation. The objective of this project was to develop a computer simulation model to predict the environmental conditions on a livestock trailer during transport of harvest-weight pigs under a typical range of climatic conditions. The results of the simulation model were used to develop recommendations for new trailer designs and management of existing trailer designs to provide the optimum environment on the trailer for finishing pigs during transport under the range of weather conditions routinely experienced in the US.

A trailer of typical current design was equipped with instrumentation in all 11 compartments to measure environmental conditions (temperature, relative humidity, air velocity, surface temperature of the inside surfaces of the trailer and of the pig, and carbon dioxide concentrations). Internal trailer, external ambient conditions, and truck speed were measured in all four seasons during journeys from the start of loading at the farm to the end of unloading at the plant under typical transport conditions. These data were used to construct a computer simulation model that predicts the conditions on the trailer for the typical range of weather and transport conditions experienced in the US. Based on the results of the computer model simulation, recommendations for improvements of current trailer designs and of transport management practices were developed.

Major findings and recommendations for improved trailer design and management approaches to reduce the variation in environmental conditions on the trailer included:

- The times when there is greatest potential for the pigs to experience thermal stress are when the trailer is stationary, either at the farm or at the plant, when air movement is low; these are times when greatest care is needed to prevent problems.
- As expected, there was considerable variation in environmental conditions on the trailer between seasons. However, there was also considerable variation within season in conditions between the decks and compartments of the trailer as well as for different times during the journey.
- Variation within the trailer in temperatures was greatest in the winter when, at the extreme, the difference between the compartments with the highest and lowest temperature was ~26°C (47°F).
- Temperatures were generally higher in the front compartments compared to other locations, which probably reflects the likely direction of air flow within the trailer (rear to front).

Suggested improvements in trailer design include:

- Varying the ventilation openings (size, shape and position) along the trailer side to produce the required ventilation rate to keep air velocity and other environmental conditions within comfortable ranges for the pig.
- Developing a system (ideally automated) for changing side wall openings based on external conditions to allow for more rapid changes in ventilation rates across all compartments in response to rapidly changing conditions that can occur during any journey.
- Installation of ventilation fans in the front end walls of the trailer to increase ventilation rates under hot conditions, particularly when the trailer is stationary.
- Establishing the heat transfer characteristics of various bedding materials to determine the most appropriate dry bedding material to use in cold weather and the most appropriate wetted bedding material to use in hot weather (to improve heat transfer via evaporation).

Further research is required to fully validate the model developed in this project. Also, future studies should focus on taking measurements at several locations within each compartment, use air velocity sensors that indicate the direction as well as the speed of air flow, and include data collected with different pig stocking densities on the trailer.

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II. Scientific Abstract:

The objective of this project was to develop a computer simulation model to predict micro-environmental conditions on a swine transport trailer during transportation from the time of loading the pigs at the farm, during the journey, to the time of unloading pigs at the plant under the range of typical external ambient conditions. A trailer of typical current design was equipped with instrumentation in all 11 compartments to measure internal temperature, relative humidity, air velocity, surface temperature of the inside surfaces of the trailer and of the pigs, and carbon dioxide concentration. Measurements were taken every 6 sec during the journey on a total of 20 loads of pigs (156 pigs/load; average live weight 132 kg; floor space on the trailer 0.48 m²/pig) under standard transportation conditions (total time from start of loading to end of unloading 5.5 hours; distance from farm to plant 220 km) in journeys in all four seasons. These data were used to construct a three-dimensional Computational Fluid Dynamic model, the results of which were used to develop recommendations for improvements of current trailer designs and transport management practices.

There was considerable variation in all environmental parameters measured on the trailer between seasons and, also, within season, between decks and compartments of the trailer, and between stages of transportation. For example, average compartment temperature during the journey were considerably lower in winter than in summer [6°C (42°F) vs. 29°C (85°F), respectively], with temperatures in the spring (17°C; 63°F) and Fall (19°C; 67°F) being intermediate and similar. The greatest variation in temperature between compartments within the trailer was observed in the winter. The compartments in the front of the trailer generally had higher temperatures than those in the rear, particularly in the winter, which reflects the likely direction of air flow from the rear to the front of the trailer. Increases in internal trailer temperature were generally greater at times when the trailer was stationary and air movement was limited, particularly during the period at the farm.

Major recommendations for improvements of trailer design based on model simulations included varying the size, shape, and/or position of the ventilation openings along the trailer side to provide the variable ventilation rates required to maintain conditions in all locations on the trailer within comfortable ranges for the pigs. Ideally, the opening and closing of the side wall openings to change air flow should be automated so that adjustments can be made more quickly in response to the rapidly changing conditions that can occur during the journey due, particularly, to changes in vehicle speed.

Further research is needed to validate the current model, to obtain more detailed measurements of the direction as well as the speed of air movement within the trailer, and to make measurements at more locations within each trailer compartment.

III. Introduction:

Loss of slaughter pigs during transport to the plant (dead, fatigued, and non-ambulatory, injured animals) continues to be a significant issue for the US swine industry, representing both a substantial economic loss and, also, a major animal welfare concern. Our research has shown a close link between the incidence of dead and fatigued pigs on arrival at the slaughter plant (Hamilton et al., 2003), suggesting some common causal factors. Metabolic acidosis resulting from the combination of stress and exercise during the transportation process has been implicated as a major factor involved in the development of fatigued pigs (Benjamin et al., 2001; Anderson et al., 2002). Metabolic acidosis is observed in pigs that are stressed during transportation, particularly as a result of factors such as bad handling practices during loading, and reduced floor space allowances and mixing of pigs from different farm groups on the trailer.

Interestingly, however, we have observed a significant incidence of fatigued pigs on arrival at the plant in situations where the animals were handled optimally both at the farm and on the trailer. Obviously, pigs that became fatigued in such situations experienced some stressful conditions during the journey that led to the fatigued condition. However, our understanding of the conditions experienced by pigs on the trailer during transport is extremely limited. The micro-climate that pigs are exposed to during transport is poorly understood but is likely to have a large impact on the stress levels experienced by the animal and, therefore, on the incidence of fatigued animals. Major environmental factors that are involved in determining the micro-climate in the trailer include temperature, humidity, air speed, air pressure, gas levels, and the amount and condition of any bedding.

Mitchell and Kettlewell (1998) found that the major stressor on poultry in transit was the thermal micro-environment and the same is likely to be true in pigs. High environmental temperature results in elevated body temperature which predisposes the pigs to becoming fatigued. In support of this, field data shows an increase in the incidence of dead and fatigued pigs during the summer months (Hamilton, unpublished). However, the incidence of transport losses can also be high under cold conditions (Hamilton, unpublished; Ritter et al., 2005). In the winter months, pigs are reared in barns at environmental temperatures generally within their comfort zone and are likely to experience cold stress when loaded and transported under low ambient temperatures. The pigs' response to cold conditions is to increase metabolic rate, thus, predisposing them to developing metabolic acidosis and to becoming fatigued. To fully understand the potential impact of environmental factors on the trailer, such as temperature and humidity, on transport losses, it is essential that the conditions experienced by pigs on the trailer across the range of weather conditions typically observed in the US are fully understood.

In previous studies, we have monitored temperature and humidity levels in a limited number of trailer compartments and have found wide variation between loads of pigs transported on trailers of the same design and, also, within loads between different compartments of the trailer. For example, in a recent study, the average temperature inside the trailer during the journey ranged from a low of -2°C to a high of 26°C for loads transported in January and July, respectively (Ritter et al, 2005). These temperatures represent a range of conditions for the pig from extreme cold stress to some degree of heat stress.

Basic differences in trailer design and management can have a profound effect on the micro-environment of the pigs. A number of European studies have investigated climatic conditions on livestock trailers during journeys to the slaughter plant. For example, Hoxey et al. (1996) showed that in poultry trailers the main ventilation flow within the trailer was from the back to the front (i.e., opposite to the direction of travel of the vehicle). Also, Kettlewell et al. (2001a) showed wide variation in temperature in different compartments of the same trailer between 6 and 9°C and, also, that these temperature differences changed over the course of a journey. In Europe, such information has been used to improve trailer designs and transport management practices (e.g., Christensen et al., 1995; Kettlewell et al., 2001b). However, trailer designs and ambient conditions are much different in Europe than in the US.

As far as we are aware, there has been no systematic investigation of the climatic environment experienced on the transport trailer by slaughter weight pigs under conditions typical of the US industry. In addition, there is limited information on the effect of trailer management (e.g, use of bedding, number of air inlets on the trailer sides open during cold weather, use of cooling systems) on the micro-environment experienced by the animal. This lack of understanding of the climatic conditions that pigs experience during transportation and of the effect of trailer design and management factors on these conditions limits our ability to provide appropriate recommendations to the industry on optimum trailer designs and management practices to minimize transport losses and ensure animal welfare.

V. Objectives:

The overall objectives of this project were:

- I. Develop a computer simulation model of transport trailers for finishing pigs that predicts the environment in the various compartments of the trailer.
- II. Based on this model, develop recommendations for new trailer designs and management of existing trailer designs (e.g., use of bedding and cooling systems, alterations of air flow) to

provide the optimum environment for finishing pigs during transport across the range of weather conditions routinely experienced in the US.

These objectives were achieved by addressing the following sub-objectives:

- i. Equip a trailer of a typical current design with instrumentation for detailed monitoring of the environmental conditions in the trailer.
- ii. Monitor environmental conditions in the trailer during transportation of finishing pigs under different weather conditions (spring, summer, fall, and winter).
- iii. Based on the data collected under Sub-objective ii., construct a computer simulation model to predict conditions on trailers of differing designs and under different climatic and management conditions (i.e., across the range of typical conditions in terms of weather, stocking density, use of bedding, cooling systems, and air inlets).
- iv. Develop industry recommendations for the design and management of trailers to optimize conditions during transport and minimize the incidence of fatigued pigs.

VI. Materials & Methods:

The research presented here represented collaboration between Animal Scientists and Agricultural Engineers, and a leading pork producer (The Maschhoffs Inc.). The project was carried out in two parts with the first part involving the equipping of a swine transport trailer with measuring equipment which was used to collect data on conditions on the trailer under typical transport conditions (Sub-objectives i. and ii. above). In the second part, these data were used to construct a computer simulation model to predict the environment on the trailer under the range of conditions experienced in the Midwest (Sub-objectives iii. and iv. above).

Measurement of Conditions on Transport Trailers

Sub-objective i. Equip a trailer of a typical current design with instrumentation to monitor in detail environmental conditions on the trailer.

Monitoring environmental conditions during transport is difficult and requires a unique system to provide accurate data that also has the ability to withstand the harsh physical environment inside the trailer. Several functional criteria must be met for an effective measurement system, including minimum interference with the loading and unloading processes, removable for cleaning, able to withstand the vibration of a moving vehicle, and minimum disturbance to the animals. Furthermore, the system must take accurate readings as close to the level of the pig as possible and be able to collect data from

multiple positions in the trailer simultaneously. The main determinants of the internal thermal environment of commercial livestock transport trailers are the external climatic conditions, ventilation regime, internal air flow patterns, and total heat and moisture production of the animals. In order to model the internal environment of current truck designs, it is necessary to measure the environmental conditions such as air movement, humidity, temperature, and ventilation rate over a wide range of external climatic conditions.

A conventional straight deck trailer owned and operated by The Maschhoff's Inc. was used in this project. This trailer had two decks with five compartments in the top deck and six compartments in the bottom deck (Table 1; Figure 1).

Compartment	Length, m	Width, m	Floor area, m ²
Top deck			
1	2.98 (9.78)	2.50 (8.20)	7.43 (80.0)
2	3.31 (10.86)	2.50 (8.20)	8.26 (88.9)
3	3.71 (12.17)	2.50 (8.20)	9.25 (99.6)
4	2.08 (6.82)	2.50 (8.20)	5.20 (56.0)
5	3.73 (12.24)	1.33 (4.36)	4.96 (53.4)
Bottom deck			
1	2.98 (9.78)	2.50 (8.20)	7.42 (79.9)
2	3.31 (10.86)	2.50 (8.20)	8.26 (88.9)
3	3.71 (12.17)	2.50 (8.20)	9.25 (99.6)
4	1.98 (6.50)	2.50 (8.20)	4.94 (53.2)
5	3.84 (12.60)	1.31 (4.30)	5.03 (54.1)
6	3.84 (12.60)	1.12 (3.67)	4.29 (46.2)

¹Values in parenthesis are in feet or feet²

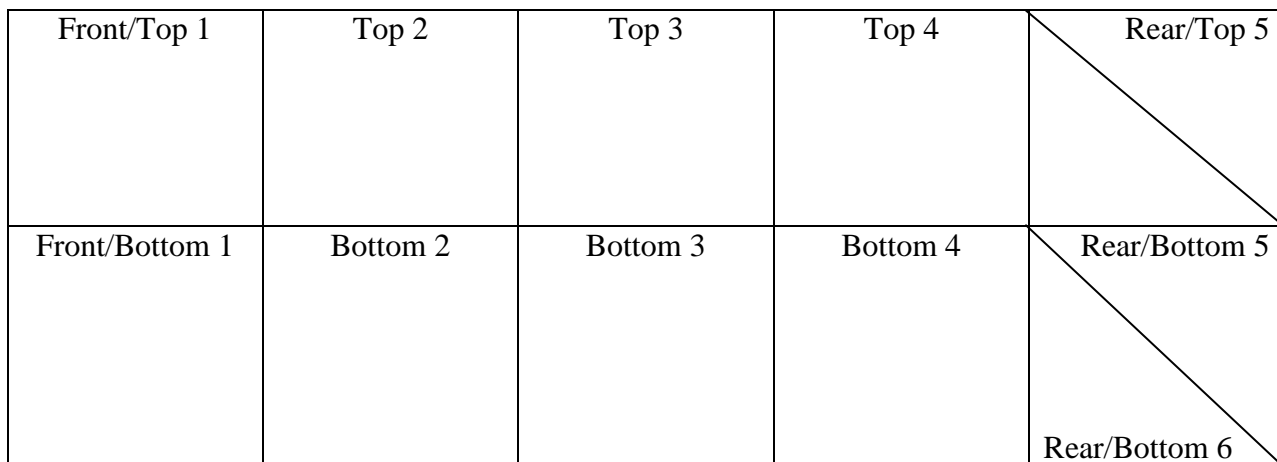


Figure 1a. Side elevation of trailer compartments



Figure 1b. Trailer used in the study

Measuring Equipment

Instrumentation was installed on the vehicle to record environmental parameters around and within the livestock trailer and details of the location and instruments used are summarized in Table 2.

The following parameters were measured in all compartments: temperature, relative humidity, carbon dioxide, and air velocity. In addition, truck speed, ambient temperature and relative humidity, solar radiation, internal surface temperatures in the trailer (in one compartment), and the skin temperatures of the pigs (in two compartments) were also measured. All electronic instrumentation on the trailer was protected by uninterruptible power supply systems.

Table 2. Parameters measured location of measurements, and instrumentation used.

Parameter measured	Number of points of measurements	Location of measurements	Instrument and model	Supplier
Temperature and humidity	12	Inside of each compartment and one point on outside of truck	HMD 50Y	Vaisala, Helsinki, Finland
Carbon dioxide	12	Inside of each compartment and one point on outside of truck	DSC 310e	Intech Controls, La Jolla, CA
Air velocity	11	Inside each compartment	Custom Built	University of Illinois, BESS Lab.
Pig surface temperature	2	In the front and rear compartments on the top deck (Compartment 1 and 5)	In-line IR sensor (Model MIL5C)	Dwyer Instruments, Michigan City, IN
Truck internal surface temperature	3	Ceiling, sidewall and front wall in the front compartment on the top deck	In-line IR sensor (Model MIL2C)	Dwyer Instruments, Michigan City, IN
Incident solar radiation	1	On roof of truck	Pyranometer (Model LI-200SA))	LI-COR, Inc. Lincoln, NE
Truck speed	1	Inside Cab	GPS tran (Model VBOX-II)	VBOX USA, Clawson, MI
Data acquisition system	N/A	N/A	Personal computer DAQ/56	IoTech, Cleveland, OH

The temperature/humidity, carbon dioxide, and air velocity sensors described in Table 2 were combined into a single sensor pack (Figure 2) which was designed to prevent damage from pig activity during transport, to ensure proper data collection, protect the sensing equipment, and to maintain animal well-being. The sensor packs were installed in all 11 compartments within the trailer (Figure 3) and were connected to a single data acquisition system that was installed in a laptop computer located in a box under the trailer during the journey. The sensor packs were hung from the top and in the middle of each compartment using angle iron bars fixed to the trailer and two metal chains, so that they were located just above the backs of the standing pigs (Figure 3). The data acquisition system was developed with the objectives of achieving a high collection frequency, rapid response time, and accurate time recording of the different events during the journey. All sensors recorded data every six seconds during the transport process (from start of loading through unloading at the packing plant).

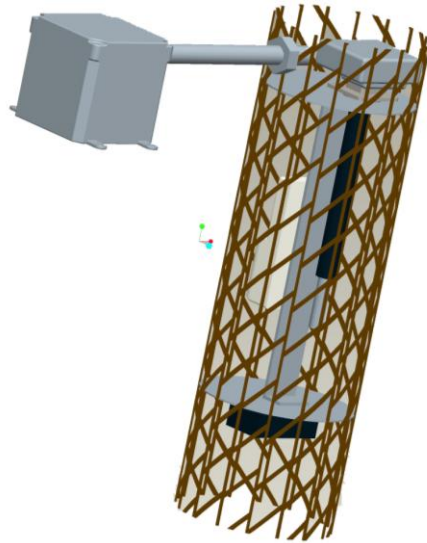


Figure 2. Photograph of a sensor pack



Figure 3. Photograph of sensor pack in one compartment of pigs during testing

Sensor Selection

Environmental measurements such as temperature and humidity are essential to determine the amount of heat lost or gained from the animal, and, also, the thermal stress on the pig. The most commonly used method to measure temperature and humidity around animals is by using small microcomputer data logger units (Hamilton et al., 2003; Lewis, 2006; Ritter et al., 2006; Stull, 1999; Wheeler et al., 2001). Data loggers, such as HOBO® (On-set Computer Corporation, Bourne, MA), are widely used because of the relatively low cost, ease of use, and ability to run independently without the need for an external power supply. We opted to use different instrumentation in the form of analog sensors connected to a single data logger system in order to achieve a high collection frequency, rapid response time, and an accurate time record for the different events throughout transport.

Two types of temperature and humidity sensors were used on the trailer. Vaisala HMD50Y (Vaisala, Helsinki, Finland) temperature and humidity sensors were used in all compartments and enclosed in the sensor packs. These sensors were factory calibrated to be accurate to $\pm 0.3^{\circ}\text{C}$ and $\pm 3\%$ relative humidity. This type of sensor was also placed outside the trailer on the top left hand side (nearest the inside of the road) to measure external ambient temperature and humidity (Figure 4). Data loggers (HOBO H8 Onset Computer Corporation, Bourne, MA) were also placed in six of the test compartments (the front 3 compartments on the top and bottom deck) to measure temperature and humidity. These data were used as a backup and to verify the measurements collected with the Vaisala sensors.

Carbon dioxide concentration and air velocity were also measured in all compartments on the trailer. The carbon dioxide sensor used was model DSC 310e (Intech Controls, La Jolla, CA). This sensor uses a non-dispersive infrared measuring method with passive diffusion sampling and, consequently, no external pump is needed to draw air into the sensor. The sensor was set at the factory to measure within a range of 0 to 5000 ppm and was powered from a 24 VDC supply. All circuitry was protected inside a plastic housing and featured an external light to indicate operation. Intec recommended calibration every three to five years, and the unit had a 0 to 10 volt analog output.



Figure 4. Placement of the external sensors on the curb-side of the trailer

The air velocity sensor was custom made by the University of Illinois Department of Agricultural and Biological Engineering using a Mass Air Flow (MAF) circuit and a glass-bead thermistor. Air velocity proved to be the most difficult parameter to measure. Several air velocity sensors are commercially available, but not many can withstand the harsh physical environment inside a commercial livestock transport trailer. Other more rugged sensors are not suitable for measuring omni-directional flows. For example, TSI Inc. (Shoreview, MN) manufactures an air velocity transducer with several different tips to allow for omni-directional measurement, which uses thermal heat loss to measure air velocity. However, this sensor is expensive and also is designed for fixed location monitoring. Due to the cost and durability constraints associated with commercially available velocity sensors, it was decided to build the air velocity sensors in-house. Details of the design and calibration of these sensors are presented in Appendix A.

Solar radiation and truck speed sensors were mounted on the roof of the trailer (Figure 4). Truck speed measurements were made using a GPSTran 5Hz Speed Sensor from Race Logic (Clawson, MI). This is a non-contact sensor that does not rely on counting tire or axle revolutions. It is a satellites-based GPSTran system that can measure speed to an accuracy of 0.1 km/h; the output is a pulse with 10 pulses per meter traveled. Ambient (outside) temperature and humidity were measured using the same Vaisala HMD50Y equipment as used inside the compartments. After the first set of hot weather loads, it was noted that the measurement of the temperature was affected by the air velocity of the moving trailer,

because of the metal casing around the sensing element. As a result, a copper-constantan thermocouple wire was installed to measure temperature. The thermocouple was calibrated using a Techno DB-35L Block Calibrator (Techne LTD, Duxford, Cambridge, England). Similar thermocouples have been used in previous studies to measure compartment temperature (e.g., Lambooy, 1988).

The incident solar radiation sensor used was the LI-200SA Pyranometer (Li-Color Bioseiences, Lincoln, NE). This required no external power and produced a linear current output via a photovoltaic cell located inside the sensor. The voltage drop across a series resistor (147 Ω) is measured by a data acquisition board with a claimed error of less than 5%. The sensor was mounted in the same plane as the roof of the trailer (Figure 4). During test loads in July, a larger resistor (604 Ω) was initially installed with the solar radiation sensor instead of the one (147 Ω) that was used at other times. Consequently, the factory calibration could not be used for the solar radiation readings taken in July. Therefore, a small-scale calibration experiment was carried out to determine the calibration constant for the values already recorded during the summer tests. For this calibration, the solar radiation sensor was fixed to a movable cart together with a Extech Instruments (Waltham, MA) Model 401025 hand-held digital light sensor. Readings were taken during different light levels in natural sunlight to determine a calibration curve.

Infrared temperature measurements of the internal surfaces of Compartment 1 on the top deck and the skin surface temperature of the pigs in Compartments 1 and 5 on the top deck were made using a Mini in-line IR sensor from Dwyer Instruments (Michigan City, IN). All three trailer surface temperature measurements were made using MIL5C sensors, which were pointed at the roof, front wall, and side wall of the trailer. The remote sensing head allowed the electronics to be safely mounted in a box, while the head could be positioned within 3 meters of the box. The sensors were powered by 24 VDC, and provided a 0 to 5 volt output with an accuracy to within 1°C. Compartment 1 used a MIL2C sensor to monitor pig surface temperature since the compartment was larger and this particular sensor has a 2:1 distance to target size ratio. Compartment 5 used a MIL5C sensor to monitor pig surface temperature because of the smaller compartment size; this sensor has a 10:1 distance to target size ratio. The skin surface temperature of the pigs that was measured by the sensors was assumed to be slightly different from the actual skin temperature due to the effect of the hairs and other material on the pigs' surface.

Sensor packs were hung in each of the 11 compartments at a height that was just above the height of the animals. Compartments varied by size within the trailer and, as a result, each sensor pack was mounted in the center of each compartment. The packs were mounted to the ceiling of each compartment via two

chains that allowed some movement of the pack. The outer wire-mesh cage of the sensor pack was designed to protect the sensors from the animals while not restricting air flow around the sensors. The wire mesh (expanded metal flooring) was 0.31 cm thick with approximately 3.5 cm x 1.9 cm diamond shaped holes. The air velocity sensor was placed at the bottom of the sensor pack in order to measure the air velocity as close to the pigs' level as possible. The temperature/humidity sensor and the carbon dioxide sensor were mounted above the air velocity sensor. The strong wire mesh cages were constructed to be able to withstand the weight of several pigs in case the chains holding the packs were to break. The bottoms of the cages were coated with a rubberizing material to prevent any damage to the pigs if they were to come into contact with the packs.

All wiring used to connect the instruments to the data acquisition system was housed within flexible plastic conduit to protect it from potentially harmful external elements, and was routed through a junction box attached to the ceiling of the trailer. The flexible conduit line also provided a third support which reduced sensor pack movement during stopping and starting of the truck.

Data Acquisition Design

Proper construction and placement of the sensor pack was the first step in building a sensing system. The second step was to develop a system to power the sensors, and to retrieve and store the data. All sensors required a 24 VDC power supply, however, the power available from the truck was 12 VDC. A SR-500 Step-Up regulator was used to convert from 12 to 24 VDC. This regulator was internally fused and was capable of handling the 3 amp power requirement. All wiring through the trailer used 6-twisted pair, individually shielded instrumentation wire. Shielded wire reduced electrical noise in the system and provided a usable signal. All wire connections were soldered to ensure proper conductance during transportation. Since the sensor packs were removed between tests, plastic connectors with metal pins were used for critical wire connections. The wire harness between the data collection box and the individual sensor packs stayed on the trailer between tests. The pin connectors were wrapped in plastic and taped to protect them during routine trailer cleaning and sanitation. After each test, dielectric grease was applied to prevent corrosion of the metal pins inside the connectors.

The output from each sensor was in the form of an analog voltage signal which was read by an IOTech Personal Daq/56 data acquisition module. The module had capacity for 60 single-ended analog signals, of which 57 were used by the sensors mounted in the trailer. Additionally, the Pdaq/56 module was able to read the pulse frequency output produced by the GPS module to measure vehicle speed. Voltage readings were taken in sequence and recorded every 6 seconds via a USB connection into a laptop

computer. Data were recorded by pDaq view (IOTech. Inc., Cleveland, OH), a data acquisition and recording program. Upon recording, pDaq view created a header file with the starting time and column labels, and recorded values throughout the test and saved these in a separate binary file. Once the data recording was completed, the two files were combined into a single text file. This file was converted using a file conversion program to provide a user-friendly spreadsheet for a variety of data analysis applications. The laptop computer in the trailer that was used to collect and store all data collected during a test journey was powered by a Power Bright 400 watt power inverter which converts 12 VDC to 120 VAC.

Equipment Testing and Calibration

All instruments were tested and calibrated in the laboratory prior to use for any data collection during transportation. In addition, several journeys with the trailer empty of pigs were carried out prior to the start of the data collection part of this project to test that all components of the data acquisition and storage system were functioning effectively. Data files that were stored in the laptop computer from any journey were checked on the next business day following data collection to identify and correct any problems.

Sub-objective ii. Monitor environmental conditions in the trailer during transportation of finishing pigs under different weather conditions (spring, summer, fall, and winter).

Data were collected on environmental conditions on the trailer under a range of conditions to determine the environmental heat demand on market weight pigs in different seasons of the year and under different trailer operating conditions. These data were used to define periods and magnitudes of potential thermal stress on the pig. The micro-environmental conditions for the pigs during transportation based on in-transit measurements in each compartment of the trailer were analyzed and were used to develop a season-specific thermal stress index for pigs that incorporated as basic inputs truck speed, presence of bedding, animal densities, percent of openings in the trailer walls, and external meteorological parameters.

Environmental heat demand is a combination of convective, conductive, and radiative heat transfer. To perform the required analysis and estimate the sensible and latent heat production of the animals, it was necessary to calculate the net air exchange rate through the vertical walls of each compartment, the air temperature, relative humidity, heat conduction to the bedding and flooring, and radiation between the individual pig and each of the compartment surfaces.

Collection of the necessary data to estimate these parameters required two types of tests. In the first test, the trailer empty of pigs with the instruments installed was transported over a range of typical speeds to estimate the air exchange rate, which involved measurement of truck forward velocity, compartment location within the trailer, and percent openings of the compartment vertical walls. The air exchange rate was measured by treating each of the eleven trailer compartments as an individual unit. This information was important to set up the computer model and was useful for the initial model calibration. In this work, the ambient air temperature, and the air velocity and temperature in each compartment were continuously measured and recorded using the instruments and data acquisition system described above. The speed of the trailer was measured using the GPS unit which was located in the cab of the truck. The ventilation rate in each compartment was estimated using the tracer gas (CO₂) method. The test was repeated three times and the mean and the standard deviation of all measurements were calculated and the data were used for model development and calibration.

The second test was conducted on routine journeys under typical transport conditions with pigs loaded at standard stocking densities in different seasons (spring, summer, fall, and winter). The test was carried out for five days in each season (one load per day for a total of 20 loads). The timing of these loads was selected so that the journeys were carried out under typical conditions for the respective season. The intention was not to use these data to evaluate seasonal differences in conditions on the truck; the number of loads involved was too small for that. Rather, the intention was to provide data to develop the model, which required measurements to be taken under the range of weather conditions typically experienced in the US. Consequently, the time of day when pigs were loaded and transported were chosen so that the necessary ambient weather conditions was most likely to be experienced. The trucks travelled directly from the farm to the plant without any unnecessary stops. Loading and transport protocols were standardized across test loads. The same loading crew was used at each site and pig density on the truck was standardized at 0.36 m²/100 kg live weight for all journeys, which is typical for this production system.

Prior to each journey, the trailer was set up based on forecasted daily temperature. Sawdust was used as a bedding material on the floor of the trailer and the proportion of the openings in the side of the trailer that were closed were adjusted according to the ambient temperature using the information presented in Table 3 which was derived from the Trucker Quality Assurance Handbook (National Pork Board, 2004).

Table 3. Truck set-up procedures during temperature extremes.

Air temperature °C (°F)	Bedding ¹	Side slats ³
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<-12.2 (<10)	Heavy	90% closed	The respective heat and moisture transfer properties
-12.2 to -6.6 (10-20)	Medium	75% closed	
-6.6 to 4.4 (20-40)	Medium	50% closed	
4.4 to 10 (40-50)	Light	25% closed	
>10 (>50)	Light	0% closed	
¹ Heavy = 3 bags/deck; Medium = 2 bags/deck; Light = 1 bag/deck [Each bag contained 0.28 m ³ (10 ft ³) of wood shavings].			
³ Calculated on a basis of 41 total equally-sized panel openings available on the truck			

of the sawdust was assessed. The following parameters were continuously measured using the data acquisition system: ambient air temperature and humidity, and air velocity, relative humidity, and temperature in each compartment. The pig surface temperature (in Compartments 1 and 5 of the top deck) and the internal surface temperature on all outside walls of Compartment 1 of the top deck were also measured using ceiling-mounted in-line infrared sensors. All measurements were recorded from before the animals were loaded onto the vehicle, during the journey, and up to the end of the unloading process at the plant with measurements being taken every 6 seconds. The process of data acquisition was continuously monitored with a laptop computer to ensure that all sensors were operating properly during the journey. After each journey, data were downloaded from the laptop computer onto a desktop computer for checking and analysis.

Information related to the specific details of each load of pigs involved in the test was recorded including: total live weight of all of the pigs in each compartment, the area of the ventilation openings that were uncovered, the amount, type, and condition of any bedding, and the use of fan cooling at the plant (the waiting area at the plant was equipped with a canopy for shade and a bank of large fans that were used during hot weather while the trailers were standing waiting to unload; Figure 5). The timing of all events on each load (loading, transport, waiting, unloading) was recorded. The collection of all data described above continued during the period that the trailer was waiting to unload at the plant, either when it was parked in the open or under the canopy with the fans operating and these data were also used in the construction of the computer model.



Figure 5a. Canopy and bank of cooling fans in waiting area at the plant



Figure 5b. Canopy and bank of cooling fans in waiting area at the plant

VII. Results:

Sensor Testing and Calibration

Most of the sensors were calibrated by the manufacturers at the factory (with specific offset and scale values) prior to delivery to the University of Illinois. The results of calibration procedures and the scale and offset values for purchased sensors are shown in Appendix B. The air velocity sensors were calibrated in the Bioenvironmental and Structural Systems Laboratory of the Department of Agricultural and Biological Engineering at the University of Illinois. A range of air velocities was applied to each sensor and the voltages produced by the sensor were recorded using the same data acquisition system as used in the trailer testing. Pressure drops across the fan chamber and individual voltage readings for each recorded speed are shown in Appendix B. Equations were fitted to each sensor for calibration using exponential trend lines.

Details of the Loads of Pigs used for Data Collection

The dates of transportation, the time of start of loading, and the distance from the farm to the plant for all loads of pigs used for data collection are summarized in Table 3. The production sites used for these loads were determined by the production system from those available at the time that data collection needed to be carried out and this dictated the distance from the farm to the plant and also the time of start of loading.

Table 3. Dates, distances and loading times for 20 test loads.

Season	Date of transportation	Distance from farm to plant	Time of start of loading	Average weight of pigs, kg
Summer	July 5, 2006	268 km	12:10 pm	134
	July 6, 2006		12:02 pm	135
	July 7, 2006		6:14 am	132
	July 13, 2006		6:14 am	134
	July 14, 2006		7:34 am	131
Fall	October 30, 2006	95 km	12:08 pm	134
	November 1, 2006		11:35 am	130
	November 3, 2006		8:13 am	125
	November 9, 2006		11:55 am	132
	November 20, 2006		10:59 am	129
Winter	January 30, 2007	224 km	7:21 am	133
	February 1, 2007		11:03 am	132
	February 7, 2007		12:02 pm	127
	February 8, 2007		12:07 pm	122
Spring	April 2, 2007	285 km	4:53 pm	130
	April 3, 2007		3:26 pm	137
	April 4, 2007		3:12 pm	135
	April 5, 2007		2:58 pm	137
	April 9, 2007		4:10 pm	134
	April 10, 2007		2:52 pm	131
Average		221 km		132 kg

The numbers of pigs loaded into each compartment on the trailer together with the floor space per pig are summarized in Table 4. The average weight of pigs transported was 132 kg and, thus, the floor space on the trailer equated to 0.36 m²/100 kg live weight, which was the target floor space on the trailer for the system that supplied the pigs.

Table 4. Compartment areas, and floor space per pig.

Deck	Compartment	Area (m ²)	Pigs per compartment	Floor space (m ² /pig)
Top	1	7.43	16	0.465
Top	2	8.26	17	0.486

Top	3	9.35	20	0.463
Top	4	5.20	11	0.473
Top	5	4.96	10	0.496
Bottom	1	7.43	16	0.465
Bottom	2	8.26	17	0.486
Bottom	3	9.25	20	0.463
Bottom	4	4.94	10	0.494
Bottom	5	4.29	9	0.477
Bottom	6	5.03	10	0.503
Total		74.30 m ²	156	Average = 0.479 m ² /pig

Environmental Conditions on the Trailer

The major objective of the data collection process, the results of which are summarized in this section, was to provide information on environmental conditions on the trailer during transport for use in the development of the computer simulation model that is described later in this report. During this measurement phase, a large amount of data relating to conditions on the trailer and ambient external conditions were collected. A summary of these data will be presented here together with some examples to illustrate the type of information that was collected.

Means for event times and the temperature and relative humidity on the trailer for the four seasons and the overall study period are presented in Table 5. In general, the event times were typical of those observed within this system with the differences in transport times between seasons reflecting the location of the farms used relative to the plant (Table 3). As expected, there were large seasonal differences in the temperature on the trailer; also, there was seasonal variation in relative humidity levels, however, this was relatively limited compared to the variation in compartment temperatures.

Table 5. Means for event times, temperature, and relative humidity for the four seasons.

Variable	Season				Overall
	Spring	Summer	Fall	Winter	
Total number of loads	6	5	5	4	20
Timing of events, minutes					
Loading	41	62	63	64	56
Waiting at the farm	8	6	8	8	7
Transport	222	197	84	187	174
Waiting at the plant	16	54	58	68	46
Unloading	32	32	42	49	38
Total transport time	319	351	256	375	322
Temperature in the trailer by event, °C					
Loading	16.4	29.2	17.8	0.6	17.6
Waiting at the farm	21.2	30.2	20.6	7.8	20.1
Transport	17.1	29.3	19.2	5.6	18.6
Waiting at the plant	20.7	30.7	20.4	6.3	19.1
Unloading	14.3	32.2	21.5	8.0	18.8
Relative humidity in the trailer by event, %					
Loading	46.8	51.0	60.2	62.1	54.4
Waiting at the farm	47.4	56.5	53.5	71.1	55.3
Transport	45.8	47.2	43.9	51.8	47.5
Waiting at the plant	45.1	39.6	43.4	60.0	47.7
Unloading	42.6	42.5	40.7	60.1	47.4

An example of data collected for temperature, and relative humidity, and air velocity in the trailer compartments, and truck speed for the load transported on July 13, 2006 is presented in Figure 6. The truck speed and air velocity graphs follow very similar patterns, with the exception of elevated air velocity readings at the end of the journey when the trailer was stationary at the plant during the time that it was parked next to the bank of fans (Figure 5). It can be seen from the truck speed graph (Figure 6) that the trailer was stationary for ~20 minutes during the journey at approximately 08:30 and that internal air movement on the trailer ceased at this time.

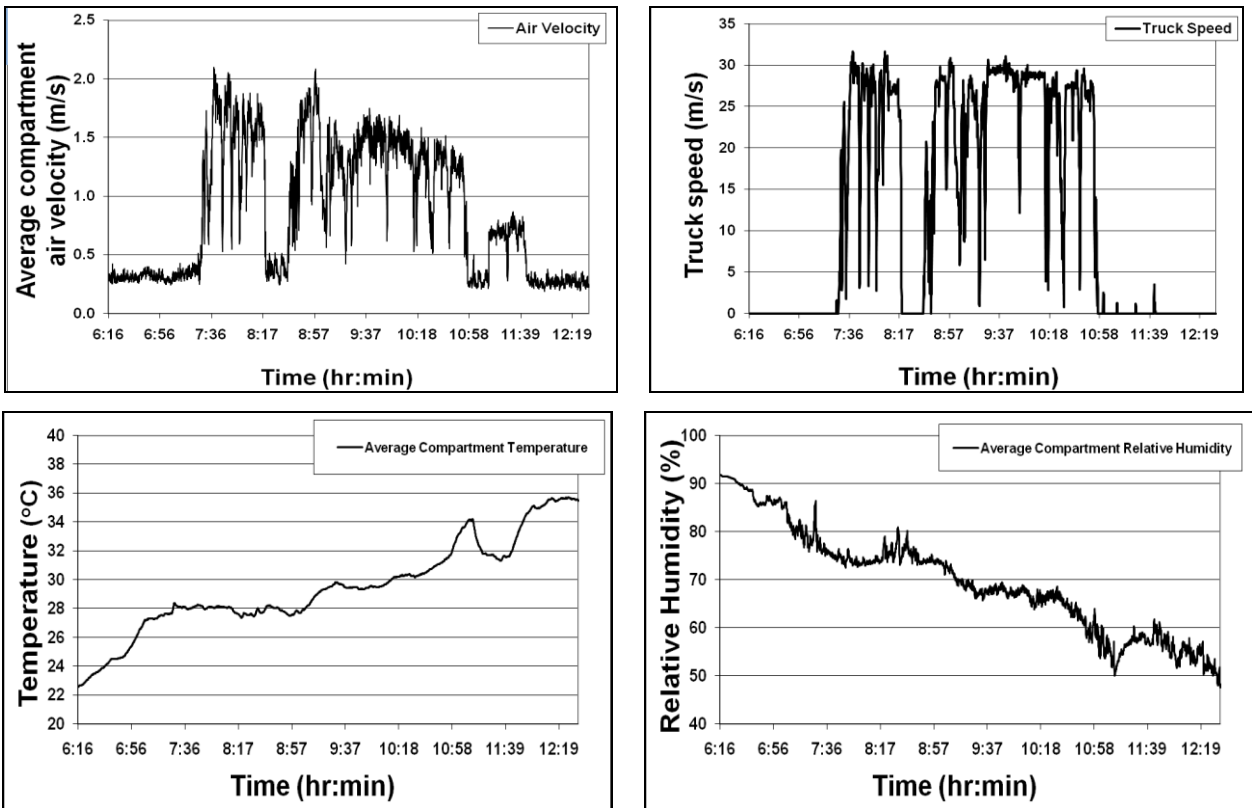


Figure 6. Truck speed, and average compartment air velocity, temperature, and relative humidity during the load transported on July 13, 2006.

[Time of: Loading: 6:16 to 7:18; Leaving farm: 7:25; Arriving at plant: 10:53; Unloading: 11:45 to 12:33]

Data on pig skin temperature and internal trailer surface temperatures recorded by the five infrared sensors located inside the trailer for the load transportation July 13th are presented in Figure 7. Two of the sensors (located in Compartments 1 and 5 on the top deck) were set up to record the skin temperature of the pigs in these compartments. There was considerable variation between consecutive measurements of skin temperature which probably reflects the movement of the animals within the compartments. Skin temperatures generally increased during the loading process and were highest while the trailer was stationary at the farm, which was at a time of low air movement on the trailer (Figure 6). Skin temperatures declined once the truck started to move and then remained relatively constant during the journey. There was a suggestion that skin temperatures increased at the end of the journey when the trailer was stationary at the plant prior to unloading at a time when air movement within the trailer was minimal (Figure 7).

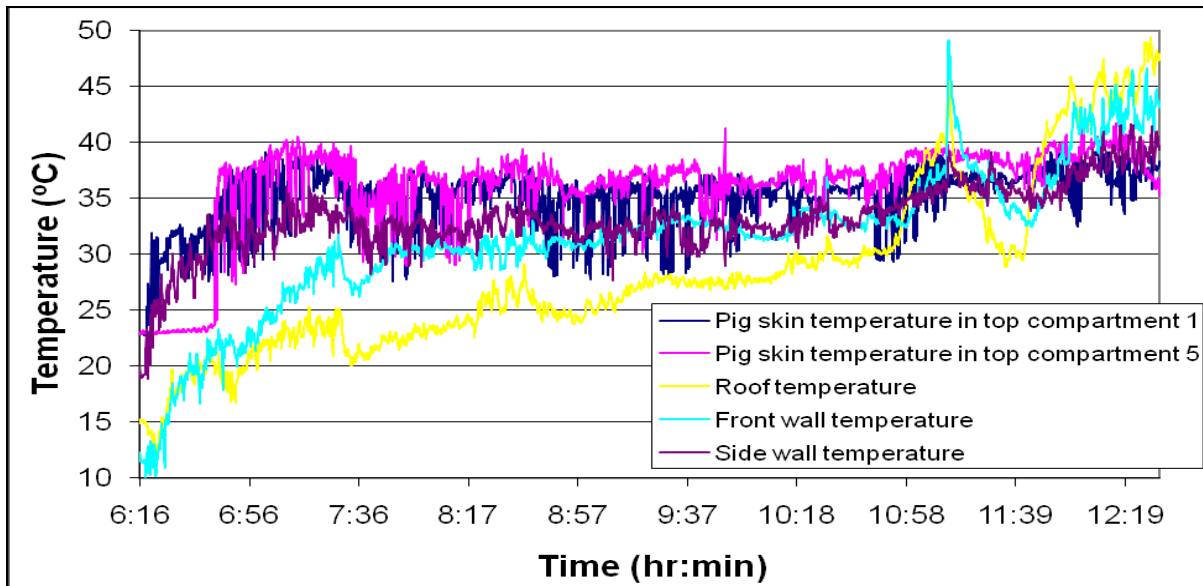


Figure 7. Infrared surface temperatures of the pigs in top deck Compartments 1 and 5, and of the roof, front and side of top deck Compartment 1 during the load transported on July 13, 2006.

The other three infrared sensors were set up to record the temperature of the inside surfaces of the truck walls at the front, side, and roof of the front compartment on the top deck of the trailer (Compartment 1). The temperature of the side wall was generally similar to the skin temperature of the pigs (Figure 7). The temperature of the front wall and of the roof of the compartment (which were also the front wall and roof of the trailer) were relatively low early in the journey but increased as the journey progressed until they were similar to the skin temperature of the pigs by the time that the truck had arrived at the plant. There was a spike in the internal surface temperature of the roof and of the front wall which corresponded to the time of arrival at the plant when the trailer was parked and before it was moved onto the bank of fans. The surface temperature of the roof and front wall also increased rapidly when the trailer was moved away from the bank of fans onto the unloading dock of the plant (Figure 7).

Carbon dioxide concentrations were measured simultaneously with temperature, relative humidity and air velocity in all compartments. The concentrations of carbon dioxide in the 11 compartments for the load of July 13th are presented in Table 6 and illustrated in Figure 8 for four of the compartments.

Carbon dioxide concentrations are a measure of ventilation rate, with higher levels in any compartment indicating lower ventilation rates.

Table 6. Mean carbon dioxide concentrations for individual compartments for the load transported on July 13, 2006.

Deck	Top	Top	Top	Top	Top	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom
Compartment	1	2	3	4	5	1	2	3	4	5	6
Location	Front	Middle	Middle	Middle	Rear	Front	Middle	Middle	Middle	Rear	Rear
Carbon Dioxide, ppm	1385 ^e	2746 ^a	1464 ^d	1079 ^g	1195 ^f	2619 ^b	993 ^h	1827 ^c	878 ⁱ	961 ^h	1101 ^g

Note: Means with different letters in the same row are significantly different ($P < 0.05$)

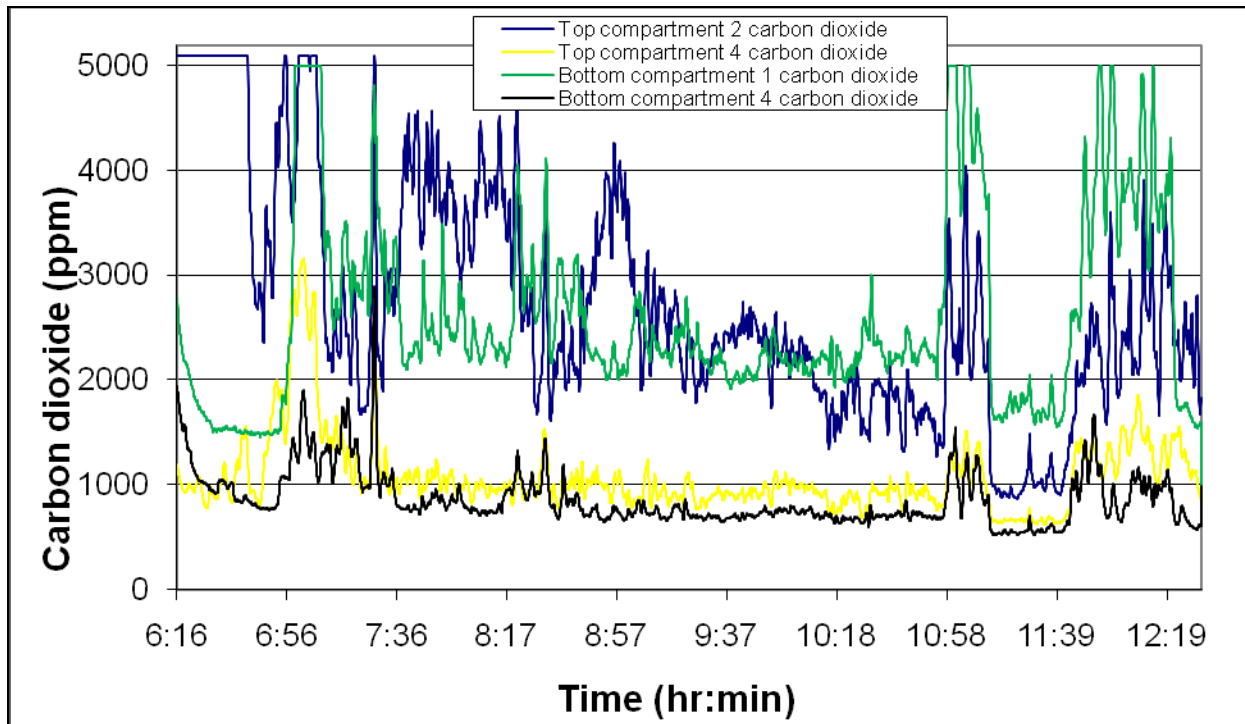


Figure 8. Carbon dioxide level in selected compartments during the load transported on July 13, 2006

The front compartments of the trailer had higher levels of carbon dioxide than the rear compartments. In studies with commercial poultry transport trailers, it has been shown that the air flow within the trailer is from the rear to front with air entering at the back of the trailer and exiting towards the front (Hoxey et al., 1996; Baker et al., 1996). If the same air flow pattern occurs in the trailer used in this study, then the higher carbon dioxide levels at the front could reflect the movement of carbon dioxide from the rear to the front of the trailer and also the low ventilation rates in those compartments.

Temperature Changes on the Trailer during Loading at the Farm

One of the most critical but poorly understood periods of the transportation process is during loading when the trailer is stationary at the farm. This is often the time when the most rapid and extreme temperature fluctuations occur on the trailer, particularly under cold conditions. This is illustrated in Table 7, where the average of the maximum difference in temperature between two compartments on the same load at the time that the trailer left the farm for the four seasons is presented. The greatest difference in average compartment temperature (20.9 °C) was observed in the winter (Table 7), with this difference being considerably lower during the other three seasons (i.e., from ~5 to 8°C).

The changes in temperatures during loading and the early part of the journey for the load transported on February 7th 2007 are illustrated in Figure 9 (the vertical line in this figure represents the time at which the truck began moving). The temperature in each compartment at the start of loading of the compartment and when the truck started to move are presented in Table 8. There was considerable variation between compartments in the extent of the temperature change from the start of loading to the time the trailer started to move, which at the extreme was 26.3°C for Compartment 1, and for the rate of temperature change which was greatest for Compartment 6 (Table 8).

The pigs used for these loads came from environmentally controlled barns where ambient temperature would generally be held at around 16 to 18°C. Obviously, the drop in temperature when the pigs are moved onto the trailer can be extreme, as evidenced by the

temperatures on the trailer at the start of loading, illustrated in Figure 8, and this dramatic drop in temperature will represent a substantial thermal stress on the animal. However, the temperature of the front compartments increased after loading and before the trailer left the farm reached levels approaching the comfort zone for pigs of the weight used in this study. However, the temperature of the rear compartments, particularly on the bottom deck, were still very low ($< 5^{\circ}\text{C}$) by the time the trailer left the farm (Figure 8) and pigs in these compartments were likely to be under considerable cold stress for the bulk of the journey to the plant.

Table 7. Average of the maximum temperature difference between two compartments on the same load at the time the trailer left the farm for the four seasons.

	Spring	Summer	Fall	Winter
Temperature difference, $^{\circ}\text{C}$	8.2	4.9	7.6	20.9

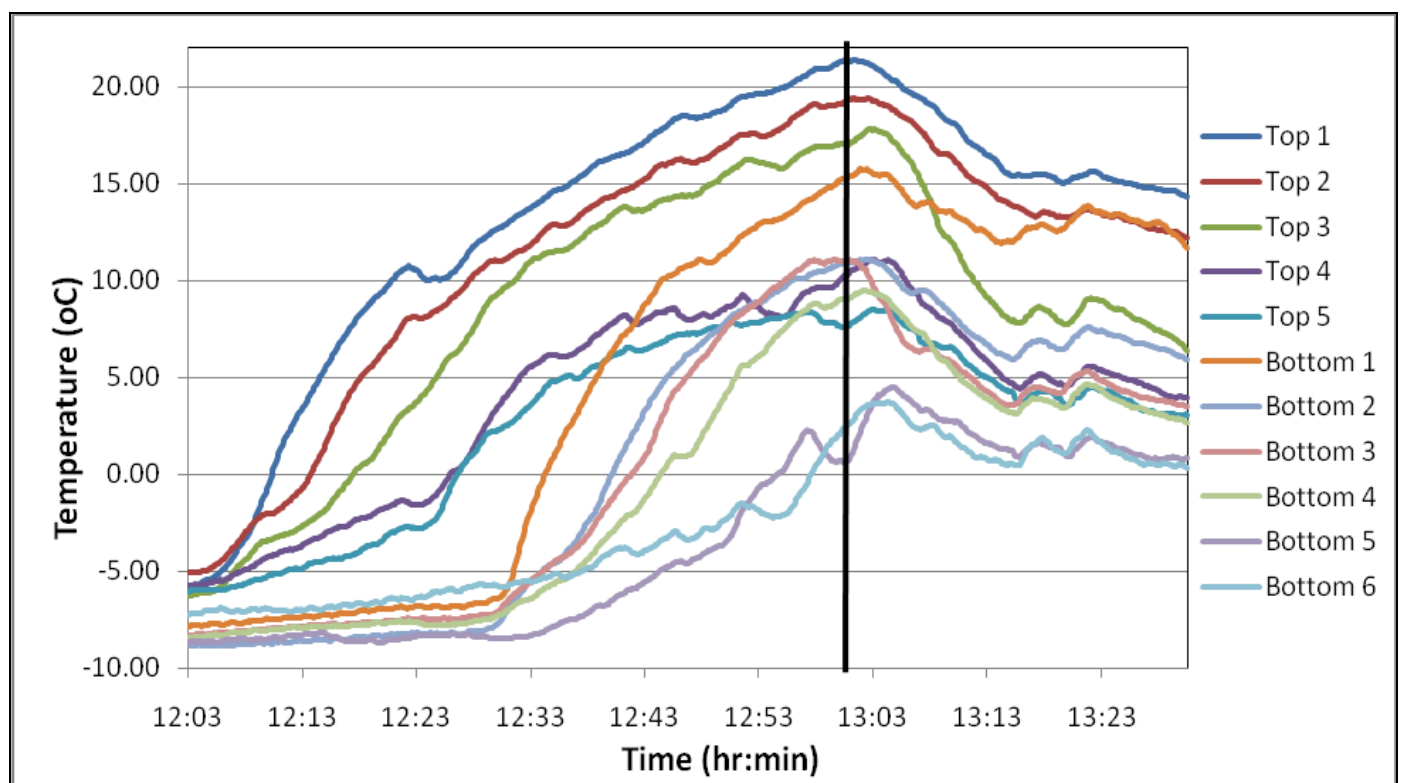


Figure 9. Individual compartment temperatures during loading, waiting at the farm, and early part of the journey for the load transported of February 7, 2007 (Vertical line at 13:00 hours represents the time when the trailer left the farm)

Table 8. Time of loading and temperature at the start and end of the loading process for the load transported on February 7, 2007.

Deck	Compartment	Time at start of loading	Temperature at start of loading (°C)	Temperature at leaving the farm (°C)	Rate of temperature change (°C/min)
Top	1	12:02	-5.9	21.4	0.47
Top	2	12:09	-2.8	19.4	0.43
Top	3	12:14	-2.5	17.0	0.42
Top	4	12:25	-1.2	10.4	0.33
Top	5	12:22	-2.8	7.7	0.28
Bottom	1	12:28	-6.8	15.3	0.69
Bottom	2	12:34	-4.8	10.9	0.60
Bottom	3	12:39	-2.7	11.0	0.65
Bottom	4	12:45	0.1	9.1	0.60
Bottom	5	12:48	-4.3	0.8	0.42
Bottom	6	12:51	-2.1	2.6	0.52

Generally speaking, the compartments on the bottom deck of the trailer showed a greater increase in temperature per unit of time during loading than those on the top deck (Table 8) which is likely to be due, in part at least, to the limited heat flow through the ceiling of the lower compartments. Heat is more easily transferred from the upper compartments through the fiberglass roof of the trailer compared to the metal decking and shavings layer between the bottom and top decks. As a result of this reduced total heat flow, the temperatures in the bottom compartment experienced a more rapid increase; however, the differences between compartments for the rate of temperature change were relatively small.

Seasonal Variation in Conditions on the Trailer

The data for the four seasons were combined and analyzed for five stages in the transportation process (loading, waiting at the farm, the journey, waiting at the plant, and unloading at the plant) and these results are summarized in Figures 10, 11, and 12 for compartment temperature, relative humidity, and air velocity, respectively.

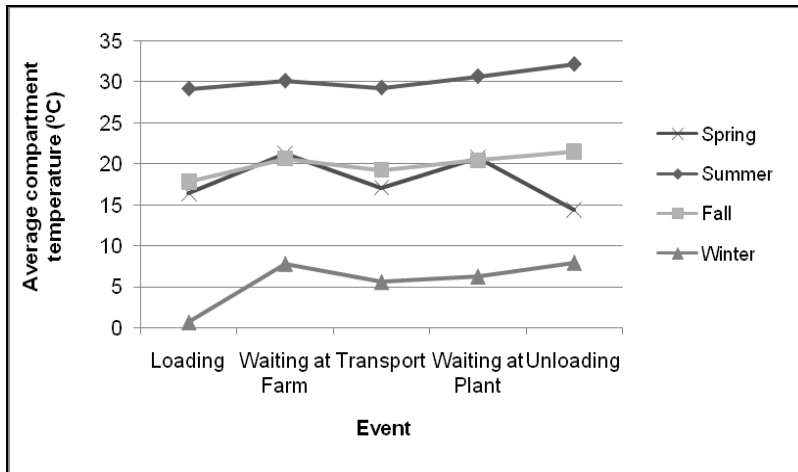


Figure 10. Average compartment temperature during journeys in the Spring, Summer, Fall and Winter seasons.

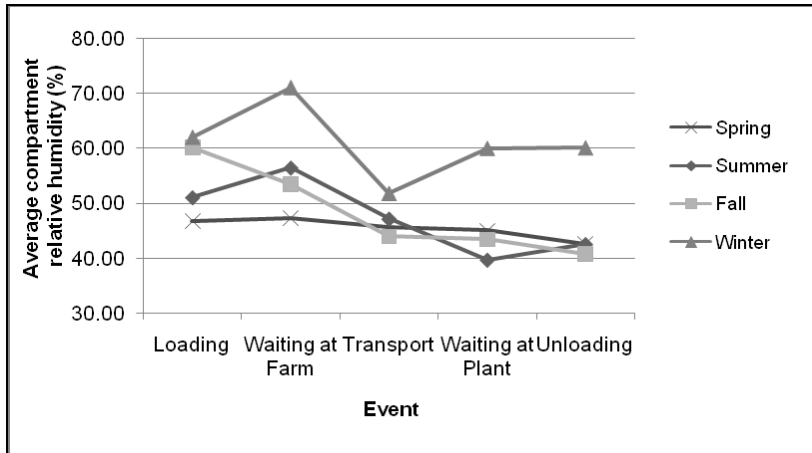


Figure 11. Average compartment relative humidity during journeys in the Spring, Summer, Fall and Winter seasons

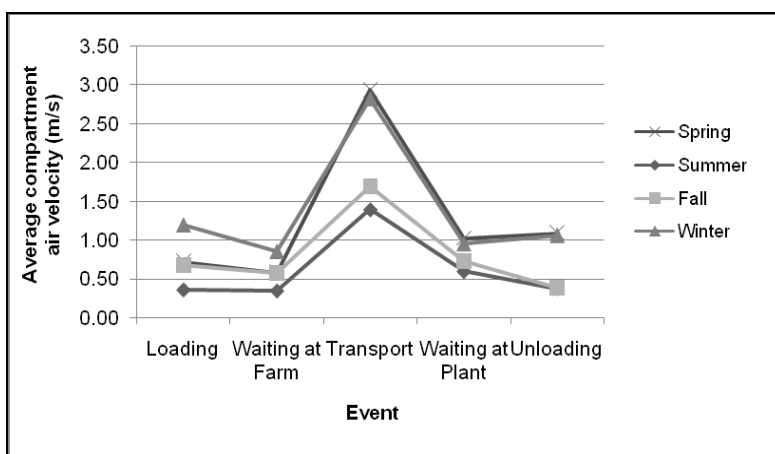


Figure 12. Average compartment air velocity during journeys in the Spring, Summer, Fall and Winter seasons.

Temperatures in the compartments generally increased during loading with the exception of the summer period when they remained relatively constant throughout the entire period of transportation (Figure 10). For the majority of the loads, the loading process started in the morning and the pigs were unloaded in early or late afternoon. As a result some of the temperature increase during the journey can be attributed to a rise in ambient temperature and not just activity from the pigs.

Relative humidity levels generally declined during the journey in all seasons; in the winter season only, relative humidity increased during the waiting period at the plant (Figure 11).

Average compartment air velocity was highest during transport which was as expected and was due to the movement of the truck (Figure 12). The higher air velocities observed in the cold season may be partly due to the heat transfer principles used by air velocity sensors. Additionally, the placement of the panels that cover the holes in the sides of the trailer may affect air movement within individual compartments and relocate the stream of ventilating air from the sides to the middle of the compartments. As a result of both of these factors, air velocity readings under cold conditions may be biased upwards; however, the general trends were still consistent across seasons.

Variation in Conditions between Compartments

Temperature, relative humidity, and air velocity for the 11 compartments in four seasons are presented in Tables 9, 10, and 11, respectively. The values reported in all three tables are the averages for all loads in each season and are for the measurements taken during the journey only, when each compartment was full of pigs (i.e., excluding loading and unloading).

Temperature, relative humidity, and air velocity varied among compartments within the trailer in each of the four seasons. The number of pigs was the same in each compartment across seasons, but the amount of bedding on the floors and the number of the holes in the trailer sides that were open or closed changed according to the external temperature.

In general, temperature levels in all seasons tended to decrease from the front to the rear of the trailer, with the greatest decreases occurring in the winter season (Table 9). In the summer season, differences in temperature among the compartments were relatively small. In the spring, summer, and fall seasons, the temperature in the compartments on the upper deck generally tended to be slightly higher than the compartment directly below. This may be due to a combination of heat rising from the bottom to the top deck and also to the incident solar radiation coming through the fiberglass roof of the trailer.

Within season, differences between compartments in relative humidity were relatively small and showed no consistent pattern (Table 10). Relative humidity levels were greater in the winter than in the other three seasons, which were relatively similar.

Air velocities during the journey for the four seasons are presented in Table 11. Top deck Compartment 1 and bottom deck Compartment 1, which are located at the front of the trailer, and top deck Compartment 5 which is located at the rear of the trailer, had some of the lowest values for air velocity in all seasons. Other compartments also had relatively low air velocities in certain seasons. For example, bottom deck Compartments 4, 5, and 6 which are located at the rear end of the trailer had low air velocities in the summer (Table 11). Generally, air velocities in the trailer were relatively higher in the spring and winter than in the summer and fall. As has previously been pointed out, air velocity values for the winter may have been biased upwards.

Table 9. Means for temperatures in individual trailer compartments for the four seasons and overall.

	Trailer compartment										
	1	2	3	4	5	1	2	3	4	5	6
Deck	Top	Top	Top	Top	Top	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom
Location	Front	Middle	Middle	Middle	Rear	Front	Middle	Middle	Middle	Rear	Rear
Spring	18.0 ^b	16.9 ^c	16.6 ^d	16.0 ^g	15.9 ^h	19.0 ^a	16.4 ^e	16.2 ^f	15.9 ^h	15.0 ^j	15.6 ⁱ
Summer	29.4 ^e	30.0 ^b	29.9 ^c	29.9 ^c	29.6 ^d	30.6 ^a	29.2 ^f	29.3 ^f	29.4 ^e	28.7 ^g	29.6 ^d
Fall	21.3 ^b	21.1 ^c	20.5 ^d	19.6 ^f	18.8 ^h	22.3 ^a	19.8 ^e	19.5 ^f	19.2 ^g	19.2 ^g	18.6 ⁱ
Winter	12.5 ^a	10.4 ^c	6.9 ^d	3.9 ^g	2.9 ⁱ	11.4 ^b	6.8 ^e	4.8 ^f	3.6 ^h	1.1 ^j	0.7 ^k
Overall	20.3 ^b	19.6 ^c	18.5 ^d	17.3 ^g	16.8 ⁱ	20.8 ^a	18.1 ^e	17.4 ^f	17.0 ^h	16.0 ^k	16.1 ^j

Table 10. Means for the relative humidity in individual trailer compartments for the four seasons and overall.

	Trailer compartment										
	1	2	3	4	5	6	7	8	9	10	11
Deck	Top	Top	Top	Top	Top	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom
Location	Front	Middle	Middle	Middle	Rear	Front	Middle	Middle	Middle	Rear	Rear
Spring	42.8 ^e	40.6 ^g	41.8 ^f	43.0 ^d	43.8 ^b	40.8 ^g	41.8 ^f	43.3 ^c	43.2 ^c	44.3 ^a	43.9 ^b
Summer	46.7 ^b	46.9 ^b	47.3 ^a	46.5 ^c	44.3 ^g	44.2 ^h	45.1 ^e	44.7 ^f	44.2 ^{g,h}	45.4 ^d	44.2 ^{g,h}
Fall	44.5 ^d	45.5 ^b	46.1 ^a	43.9 ^e	44.7 ^{c,d}	43.5 ^g	42.7 ^h	43.8 ^{e,f}	43.6 ^{f,g}	44.9 ^c	43.7 ^{f,g}
Winter	61.8 ^a	58.4 ^b	56.3 ^c	53.1 ^e	53.4 ^d	51.0 ^h	49.8 ^j	51.7 ^{f,g}	50.4 ⁱ	51.5 ^g	51.9 ^f
Overall	48.9 ^a	47.8 ^b	47.9 ^b	46.6 ^c	46.5 ^c	44.9 ^f	44.8 ^f	45.8 ^d	45.3 ^e	46.5 ^c	45.9 ^d

Table 11. Means for the air velocity in individual trailer compartments for the four seasons and overall.

	Trailer compartment										
	1	2	3	4	5	1	2	3	4	5	6
Deck	Top	Top	Top	Top	Top	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom
Location	Front	Middle	Middle	Middle	Rear	Front	Middle	Middle	Middle	Rear	Rear
Spring ¹	3.13 ^c	3.96 ^a	2.86 ^d	3.46 ^b	1.45 ⁱ	0.01 ^j	2.13 ^{g,h}	2.58 ^e	2.15 ^g	2.08 ^h	2.34 ^f
Summer	0.31 ^j	1.96 ^c	2.13 ^b	1.11 ^e	0.80 ^h	0.64 ⁱ	3.10 ^a	1.25 ^d	0.28 ^k	0.86 ^f	0.84 ^g
Fall	0.59 ^g	1.86 ^a	1.10 ^e	1.59 ^c	0.91 ^f	0.48 ^h	1.86 ^a	1.10 ^e	1.59 ^c	1.09 ^e	1.81 ^{a,b}
Winter	1.42 ^g	1.06 ⁱ	3.53 ^c	3.98 ^b	1.37 ^{g,h}	0.47 ^j	1.33 ^h	2.21 ^f	2.38 ^e	2.47 ^d	4.10 ^a
Overall	1.15 ⁱ	2.31 ^c	2.53 ^a	2.48 ^b	1.12 ^j	0.44 ^k	2.04 ^e	1.91 ^f	1.45 ^h	1.60 ^g	2.16 ^d

¹Due to equipment malfunction, the mean for Compartment 1 on the bottom deck is based on two loads only.

VIII. Construction of a Computer Simulation Model to Predict Conditions on the Trailer during Transport

Sub-objective iii. Based on the data collected under Sub-objective ii, construct a computer simulation model to predict conditions on trailers of differing designs and under different climatic and management conditions (i.e., across the range of typical conditions in terms of weather, stocking density, use of bedding, cooling systems, and air inlets).

A three-dimensional Computational Fluid Dynamic (CFD) model was developed to predict conditions (i.e., the air velocity, and temperature and moisture variations) in all compartments on the trailer. The data collected during the journeys with the trailer loads of pigs described above was further analyzed and used to construct the model. The overall purpose of the model was to predict internal environmental conditions in the compartments during a typical journey for a given set of ambient weather conditions, animal density, bedding type, and sidewall openings. The environmental factors which influence thermal comfort of animals and which were incorporated into the model include: dry bulb temperature, humidity, air velocity, floor heat conduction, and trailer roof and wall surface temperatures (for radiation heat exchange).

The governing equations used in the model included air and moisture mass balances, conservation of energy, and momentum. For each compartment, the mass energy and water vapor balance equations were solved for specific external conditions with the model transfer functions. Swine heat and moisture production were estimated by way of published models on heat production, based on micro-climate conditions in the trailer.

The model outputs were the temperature, humidity, mean air velocity, and carbon dioxide concentrations within each compartment. From these values, the effective environmental temperature, single-pig environmental heat demand, and transport heat stress index were calculated. The results from the model were compared with the measurements made at full scale during a journey to calibrate the model by modifying various model parameters.

A complete journey from farm to a slaughter house was simulated by applying this model to a series of varying external conditions to calculate the steady state internal

environmental parameters for each set of conditions. By changing the model inputs, this model can be used to evaluate different trailer modifications and management practices, and, thereby, make recommendations for the industry relating to improvements to trailer design and management.

Simulation of Trailer for Swine Transportation

A commercial CFD program, Gambit and Fluent (Fluent, Inc., NH), was used as a grid generating tool and a numerical solver. Tecplot (Tecplot Inc., WA) was used to handle the post-process work. The simulation was conducted on a supercomputing system at the University of Illinois.

i. Geometric Model

The geometry model was constructed for an aluminum straight dual-deck trailer. The interior dimensions of the trailer were 2.496 m × 2.794 m × 15.818 m (width × height × length). There were five compartments in the top deck, and six compartments in the bottom deck. The configuration of the compartments is shown in Figure 13; a photograph of the actual trailer used to collect the data for the model construction is presented in Figure 1.

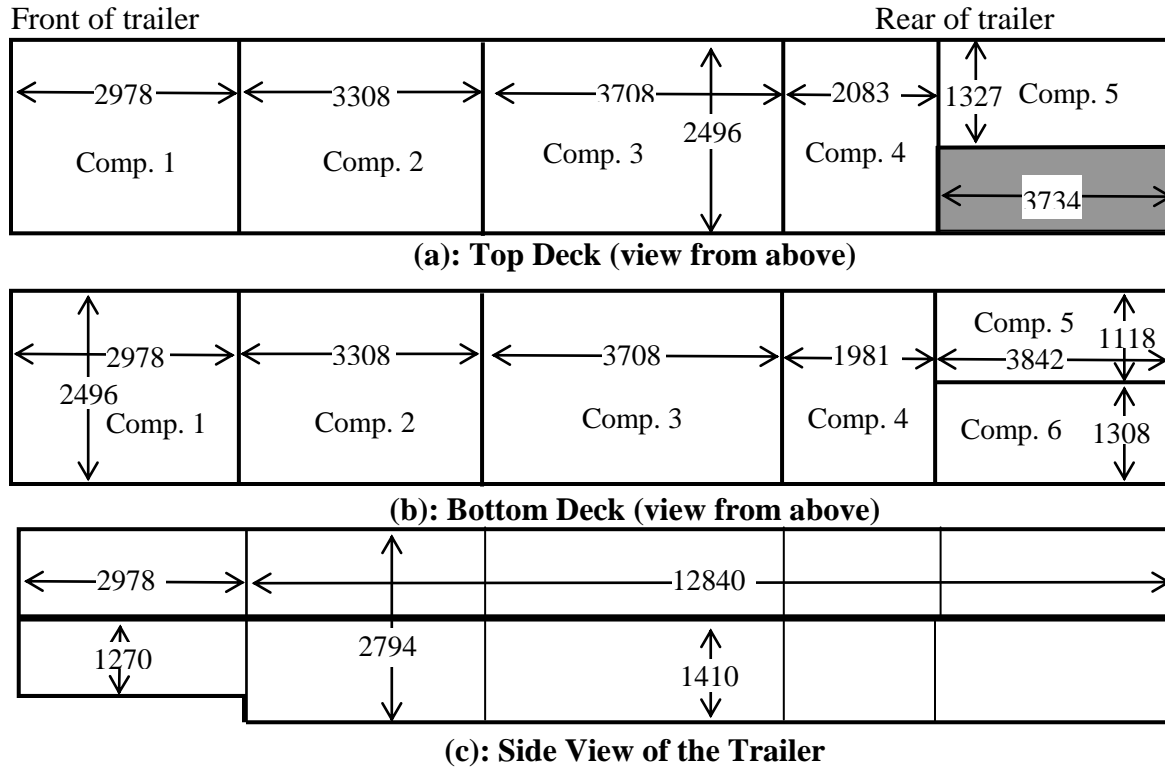


Figure 13. Configuration and dimensions (mm) of the compartments: (a) the top deck; (b) the bottom deck; (c) side view of the cross section of the trailer.

The actual geometry model for the simulation is shown in Figure 14. The origin of the geometric coordinate system is located at the intersecting point of the front and side panels and the floor of the bottom deck. The X axis is along the length of the trailer from the front to the rear. The Y axis is along the width of the trailer from the left side (curb side) to the right side of the trailer. The Z axis is along the height of the trailer from the bottom to the top.

To facilitate model development a number of simplifications were made as follows:

- The openings in the panels on each side of the trailer were considered to be a single rectangular window with the bottom of the window at the level of the back of the pig and with an area equal to that of the total area of all of the perforated holes in the side of the particular compartment.
- The rear end of the trailer was assumed to be closed with no opening.
- The pigs in all compartments were assumed to be solid rectangular blocks.

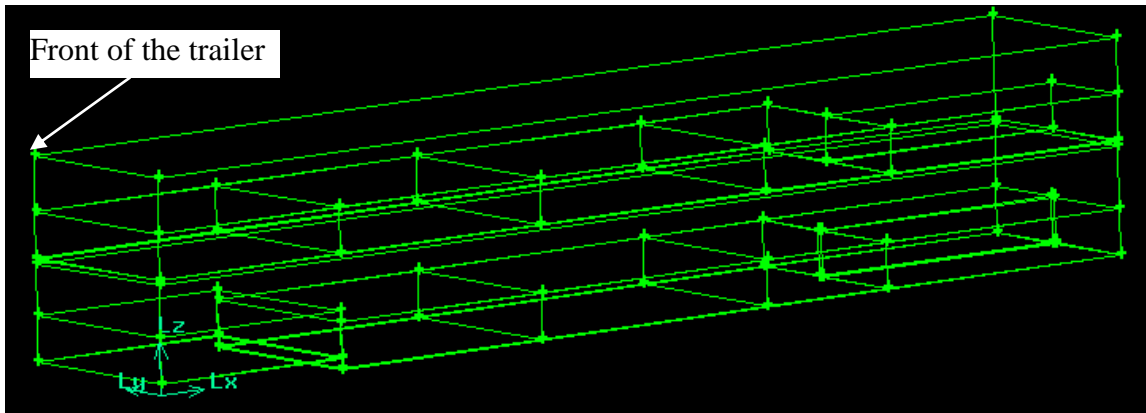


Figure 14. Geometry model established with Gambit software program for the simulation

Mesh Parameters

The mesh parameters usually include the shapes of the elements, total numbers of the elements and nodes, and the maximum element volume. These parameters have some influence on the simulation.

It is widely believed that the Navier-Stokes equations govern the detailed behaviors of a fluid flow. Unfortunately, there is no analytical solution even for the simplest turbulent flows. The computing cost to solve the full Navier-Stokes equations using direct numerical simulation (DNS) is too prohibitive at present, and DNS is not practical for industrial flows. The engineering computation of turbulent flows, therefore, relies on simpler approximation approaches, such as the Reynolds-Averaged Navier-Stokes equation models and large eddy simulation. In order to analyze fluid flows, flow domains are split into smaller sub-domains (made up of geometric primitives like hexahedra and tetrahedra in three-dimensions, and quadrilaterals and triangles in two-dimension) and discretized governing equations are solved inside each of these portions of the domain. The solution across the common interfaces between two subdomains must be continual, so that the approximate solutions inside various portions can be put together to give a complete picture of fluid flow in the entire domain. Each of these sub-domains is known as an element or cell, and the collection of all elements is known as a mesh or grid. To generate any Computational Fluid Dynamic mesh, object-defining nodes are

first created, a surface mesh is generated from the nodes, and finally a volume mesh is generated from the surface mesh.

In this study, the mesh generated for simulating the airflow field in the trailer had 541416 nodes, and 497450 elements and the maximum element volume was $1.31 \times 10^{-4} \text{ m}^3$. Generally speaking, the smaller the element volume, the more accurate the simulation results, but the more computing power and cost required.

Assumptions for the Boundary Conditions

Boundary conditions specify the flow and thermal variables on the boundaries of the physical trailer model. The pigs were assumed to be a rectangular block with a height of 0.58m (1.9 ft) from the floor and the length and width of each individual compartment, occupying the total space from the floor. The upper surface of the blocks was assumed to have a uniform temperature throughout the compartments. The air close to the surfaces of the pigs was assumed to have uniform water content, and a uniform carbon dioxide concentration.

Conditions during Transportation:

Since the direction of the external air movement (wind) relative to the trailer changes frequently during transportation, and the wind speed is generally relatively small compared with the speed of the trailer, it was assumed that the ambient air was still, and the trailer was moving at a constant speed of 26.8 m/s (60 miles/hour). The turbulence intensity of the wind relative to the trailer was fixed at 5%. The turbulence intensity is defined as the ratio of the standard deviation of wind speed to the mean wind speed.

The truck and trailer model was built with the above conditions and the simulations carried out to obtain the pressure profile around the trailer. The pressure profile is the wind pressure distribution along the two sides of the moving truck and trailer body. The pressure profiles on both sides of the trailer were then used as the boundary condition of the side windows of the trailer for simulating the interior environment of the trailer during transportation. The open windows of the trailer geometry model were set

as outlet vent boundary conditions with a specified loss coefficient and ambient pressure and temperature. The loss coefficients were set to 0 for a hot day with the side holes fully open, 13 for a mild day with the side holes 25% closed, and 26 for a cold day with side holes 50% closed. The loss coefficient relates the air speed to the pressure loss of the airflow passing the openings. Therefore, it is an indication of the resistance that airflow encounters when it is flowing through the open windows, which can be partially blocked with side slats.

Waiting at Farm and Plant:

The openings on the left side of the trailer were assumed to be a velocity inlet with a consistent airflow stream flowing in and the openings on the right side of the trailer were assumed to be the out-flow for the air.

1. Mathematical Mode: K-ε Turbulence Model; Convection and Diffusion Equation (Temperature, Moisture, Carbon Dioxide)

The three-dimensional Computational Fluid Dynamic model was established to model the velocity, turbulent characteristics, temperature, carbon dioxide and moisture spatial distributions of the internal environment of the trailer.

The model was defined by the following equations:

Conservation of mass (Dry air): (Conservation of mass, the net mass outflow of dry air from an element of air fluid must be zero):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 \quad (1)$$

Conservation of air momentum: (Conservation of air momentum, the application of Newton's second law of motion to an element of air fluid):

$$\frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \nabla \vec{U} = -\frac{\nabla P}{\rho} + \nu \Delta \vec{U} + \beta (\vec{g} - T_0 \vec{g}) + \nabla \cdot \vec{R} \quad (2)$$

Conservation of energy:

$$\frac{\partial T}{\partial t} + \vec{U} \cdot \nabla T = \gamma \Delta T + \nabla \cdot \vec{R}_\theta + S_T \quad (3)$$

Conservation of moisture:

$$\frac{\partial C_m}{\partial t} + \vec{U} \cdot \nabla C_m = D_m \Delta C_m + \nabla \cdot \vec{R}_m + S_m \quad (4)$$

Conservation of carbon dioxide:

$$\frac{\partial C}{\partial t} + \bar{U} \cdot \nabla C = D\Delta C + \nabla \cdot \bar{R}_c + S_c \quad (5)$$

where:

- \bar{U} : Velocity at spatial point $\bar{x}(x, y, z)$ and time t ;
- P : Pressure;
- ρ : Density of dry air;
- T : Temperature;
- C : Concentration of carbon dioxide;
- C_m : Concentration of moisture;
- β : Volumetric thermal expansion coefficient;
- ν : Kinetic viscosity coefficient;
- γ : Thermal diffusivity coefficients;
- D : Carbon dioxide diffusivity coefficient;
- D_m : Moisture diffusivity coefficient;
- S_T, S_m, S_C : Sources term;
- R, R_θ, R_C, R_m : Turbulent fluxes.

In the above equations, source terms S_T, S_m, S_C for heat, moisture and carbon dioxide need to be defined. Furthermore, approximate closure models should be adopted for turbulent fluxes R, R_θ, R_C, R_m . In this project, RNG $k - \varepsilon$ models with standard wall functions were used. The simultaneous equations above have no analytical solutions, and direct numerical simulation to solve the equations is prohibitive at present due to the high computing power requirement. The computing power limitation of direct simulations was addressed by using simpler mathematical flow models combined with experimental validation. The RNG $k - \varepsilon$ model is frequently used for indoor airflow field simulations; its simulation result agrees well with experiment data. The standard wall functions bridge or link the solution variables at the near-wall elements and the corresponding quantities on the wall without the requirement of fine mesh near the walls, and decrease the computational burden.

Simulation Case Studies

The model developed can be used to simulate an infinite number of conditions during transportation. However, for the purpose of this report, the model was used to simulate conditions on the trailer for three kinds of weather conditions (hot, mild, and cold) and

three different times during transportation (waiting at the farm, during transportation, and waiting at the plant). For the periods of waiting at the farm and the plant, the simulations were carried out with and without external fans blowing air through the trailer as shown in Figure 5. A summary of the resultant 15 simulations that were carried out is presented in Table 12.

Table 12. Summary of model simulation and assumed ambient conditions.

Simulation	Location	Weather conditions	External fans	Temperature, °C	Ambient condition	
					Relative humidity, %	Carbon dioxide concentrations, ppm
1	Journey	Hot	No	26.3	79.4	998
2	Waiting at the farm	Hot	No	27.5	73.1	728
3	Waiting at the farm	Hot	Yes	27.5	73.1	728
4	Waiting at the plant	Hot	No	32.5	52.1	712
5	Waiting at the plant	Hot	Yes	32.5	52.1	712
6	Journey	Mild	No	8.4	33.9	1014
7	Waiting at the farm	Mild	No	8.7	45.2	915
8	Waiting at the farm	Mild	Yes	8.7	45.2	915
9	Waiting at the plant	Mild	No	14.6	29.8	1025
10	Waiting at the plant	Mild	Yes	14.6	29.8	1025
11	Journey	Cold	No	-6.1	57.0	1622
12	Waiting at the farm	Cold	No	0.7	86.0	2438
13	Waiting at the farm	Cold	Yes	0.7	86.0	2438
14	Waiting at the plant	Cold	No	-3.1	70.0	1616
15	Waiting at the plant	Cold	Yes	-3.1	70.0	1616

Results of Simulations

The model outputs include internal trailer air velocity, temperature, relative humidity, and carbon dioxide concentration. These have been presented as “contour maps” for both the

central cross section along the longitudinal axis of the trailer and also for the central cross section across the transverse axis of the trailer in each compartment. These contour maps are presented in Appendix C for all 15 of the simulations described in Table 12; selected results from these simulations are summarized below.

Airflow patterns

The airflow patterns when the truck was moving on a hot day (with zero wind) in the longitudinal and transverse cross-sections through the trailer are shown in Figures 13 and 14, respectively. The direction of the arrows on the dashes in the diagram indicate the direction of air flow. Ambient air entered the trailer through the openings in the sides of the compartments in the rear and center of the trailer and exits through the side opening in the front of the compartment (Figures 13 and 14).

Environmental conditions on the trailer during transport on hot, mild, and cold days (Simulation 1, 6, and 11, respectively).

Air velocity within the trailer (Figure 15a) generally increased from the rear through the center and towards the front on both decks of the trailer under hot, mild, and cold conditions. However, there were pockets of very low air movement at the front end of the trailer under all weather conditions. The areas of the trailer with the greatest air velocities under hot conditions were towards the front on both decks, and the areas with the greatest air velocities under mild and cold conditions were on the top deck in the middle/front of the trailer (Figure 15a). Air velocities in the trailer were generally lower under mild and, particularly, cold conditions; however, they did exceed 5 meters/second in some compartments under cold conditions which is in excess of 10 miles/hour. Such air speeds can add a wind chill factor, particularly under cooler conditions.

Model simulations showed relatively limited variation in temperatures on the trailer during hot conditions (Figure 15b). Variation in temperature along the trailer was relatively greater during mild and, particularly, under cold conditions where there were areas of the trailer, particularly on the top deck, that were below 0°C and other areas, such as at pig level on the lower deck, in excess of 15 to 20°C (Figure 15b).

The simulations for relative humidity levels on the trailer during transport are illustrated in Figure 15c. Under hot conditions, relative humidity levels were relatively uniform along the trailer on both decks and were generally within the range 65 to 70%. During mild conditions, relative humidity levels were low (<50%) and were consistently lower on the bottom than on the top deck. During cold conditions, relative humidity levels were relatively uniform on the bottom deck and were generally within the range 45 to 55%; on the top deck, however, there were areas of higher relative humidity ($\geq 65\%$), particularly at the level of the pigs (Figure 15c).

Thus, the model simulation results for conditions on the trailer during the journey clearly show that the main environmental parameters (air velocity, temperature, and relative humidity) vary considerably not only with outside ambient temperature conditions but also showed large variation along the trailer within a particular season. For example, in hot conditions, although temperatures were relatively uniform along the trailer, air velocities showed large variation along the trailer, with areas of very low air movement. In cold conditions, temperatures on the trailer were generally low and very variable which when combined with air velocities and relative humidities that were relatively high in some localized areas of the trailer could result in a large number of pigs being cold stressed during the journey.

The results of model simulations for air velocity across the transverse plane of every compartment of the trailer during transport on hot, mild and cold days are illustrated in Figures 15d, 15e, and 15f, respectively. Air velocity across the transverse plane on a hot day showed considerable variation both between and within compartments (Figure 15d), being lowest for the rear compartments, particularly on the bottom deck. Compartments 1, 2, and 3 (bottom deck) showed the greatest variation across the transverse plane (Figure 15d). Under mild conditions, air velocity across the transverse plane was relatively low and uniform for compartments on the lower deck (Figure 15e). Under cold conditions, air velocity on the bottom deck was relatively variable for some compartments (Figure 15f).

Air temperatures across the transverse plane of trailer compartments for hot, mild, and cold conditions are presented in Figures 15g, 15h, and 15i, respectively. Generally speaking, variation in temperature across all compartments and for the three external ambient conditions was relatively limited.

Relative humidity levels across the transverse plane of trailer compartments are illustrated in Figures 15j, 15k, and 15l, respectively. Generally speaking, relative humidity levels showed limited variation across the compartments under hot conditions (Figure 15j). Under mild conditions, there was an area of high relative humidity above the pigs in the front compartment on the lower deck; however, elsewhere on the trailer relative humidity levels were relatively constant across the trailer (Figure 15k). Under cold conditions, there were areas of high relative humidity across compartments on the top but not on the bottom deck (Figure 15l).

Environmental conditions on the trailer during the period that the trailer was waiting at the farm on hot, mild, and cold days (Simulations 2, 7, and 12, respectively)

As expected, air velocity in the trailer during the period when the trailer was stationary at the farm was very low (Figure 16a). Temperature on the trailer was high under hot conditions and would be within the range considered to be a heat stress for the pig, particularly on the bottom deck (Figure 16b). Under mild and cold conditions, temperatures on the bottom deck were again higher than on the top deck. Under cold conditions, temperatures were generally well below the pigs comfort zone. Relative humidities were much higher when the trailer was stationary at the farm (Figure 16c) than during the transport (Figure 15c) and were in excess of 90% in many locations and for all three weather conditions. Generally speaking, humidity levels were higher on the top than on the lower deck under hot and mild conditions, while the reverse was the case under cold conditions, although, there were pockets of high relative humidity on both decks under all three weather conditions.

Thus, as expected, the major problem while the trailer is stationary at the farm is under hot conditions when the potential for heat stress the pig is high due to the combination of

high temperatures, very low air movement, and high relative humidity. However, relative humidity levels were high under other weather conditions which when combined with low temperatures on the trailer during cold conditions could add to the cold stress on the pigs.

Environmental conditions on the trailer during the period that the trailer was waiting at the plant on hot, mild, and cold days (Simulations 4, 9, and 14, respectively)

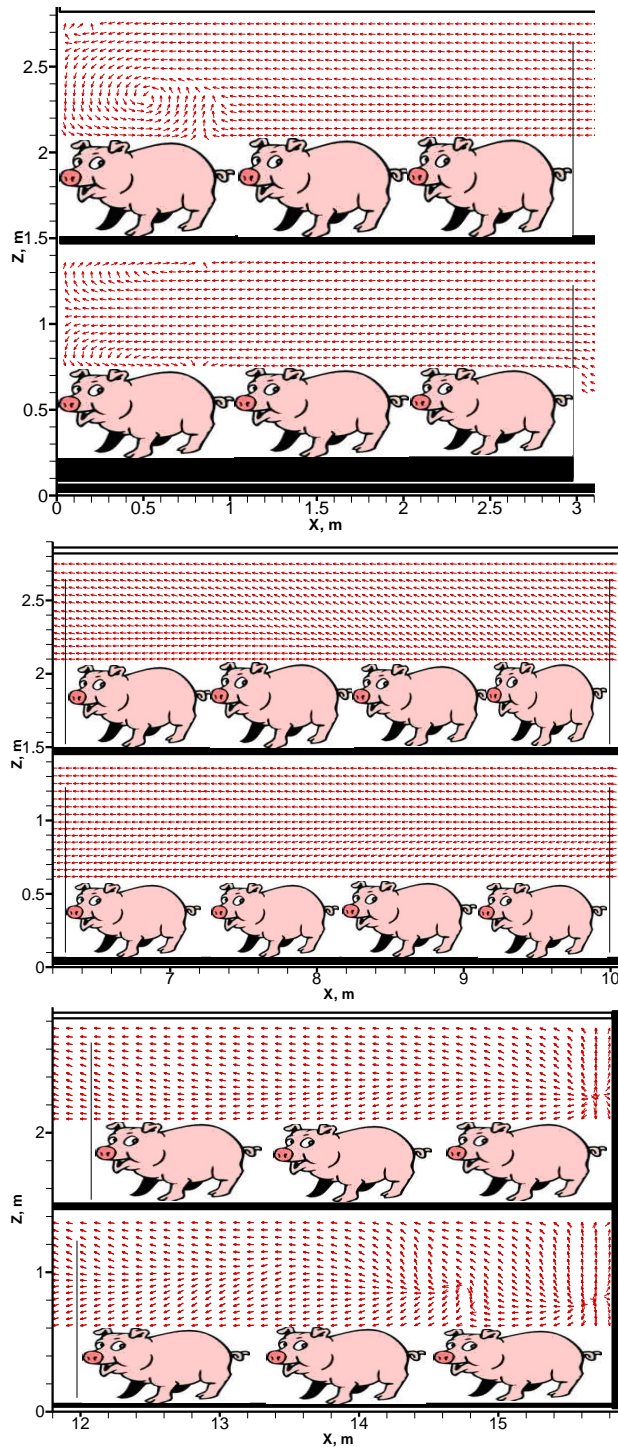
The results of model simulations for the period when the trailer was stationary at the plant after the journey but before unloading are summarized in Figures 17a, 17b, and 17c. In these simulations, it was assumed that the trailer was not being ventilated by the bank of fans (Figure 5). The results of these simulations are very similar to those for the period when the trailer was stationary at the farm. Thus, air velocity within the trailer was very low under all weather conditions (Figure 17a). Temperature within the trailer was very high under hot conditions and relatively high in some compartments, under mild conditions, particularly, on the lower deck in the front and middle of the trailer. Under cold conditions, trailer temperatures were low in all compartments (Figure 17b). Relative humidity was moderate under hot conditions but relatively high on the top deck of the trailer under mild conditions and on large parts of both decks under cold conditions (Figure 17c).

Thus, the major concerns for the pigs while the trailer is stationary at the plant is the potential for heat stress under hot conditions but also under mild conditions where the combination of moderately high temperatures and high humidity levels could result in problems. Conversely, under cold conditions the potential for cold stress in the pigs is high due to the combination of low temperatures and high relative humidities in the trailer.

To counteract the potential problem with heat stress during the period that the trailer is stationary at the plant, a canopy and bank of fans had been installed in the holding area for the trailers (Figure 5). The effect of running the fans only was simulated using the model and the results of these simulations (i.e., Simulations 5, 10, and 15) are illustrated

in Figures 18a, 18b, and 18c. As expected, running the fans increased air velocity in the trailer, substantially under hot conditions, but to a very limited degree under mild and cold conditions (Figure 18a). The reason for this relatively limited effect is due to the fact that some of the openings in the sides of the trailer would be closed under mild and cold conditions. In practice, the fans would only be used under hot conditions and, therefore, the results of the simulations for mild and cold days will not be discussed. Running the fans under hot conditions reduced the temperature within the trailer by 2 to 3 °C (Figures 17b and 18b) and also reduced the relative humidity on the trailer to a relatively greater extent (Figures 17c and 18c). Thus, these model simulations would suggest that using these fans when the trailer is stationary at the plant would reduce the heat stress on the pigs. However, the temperature in the trailer when the fans were running was still relatively high (Figure 18b) and at a level at which most of the pigs on the trailer could be heat stressed.

Figure 13. Airflow patterns through the longitudinal section in the center of the trailer during transport.



[In this and subsequent Figures, X is the length of the trailer measured from the front, Y is the width of the trailer measured from the left-hand (curb) side, and Z is the height of the trailer measured from the bottom.]

Figure 14. Airflow patterns through the transverse sections of the trailer during transport.

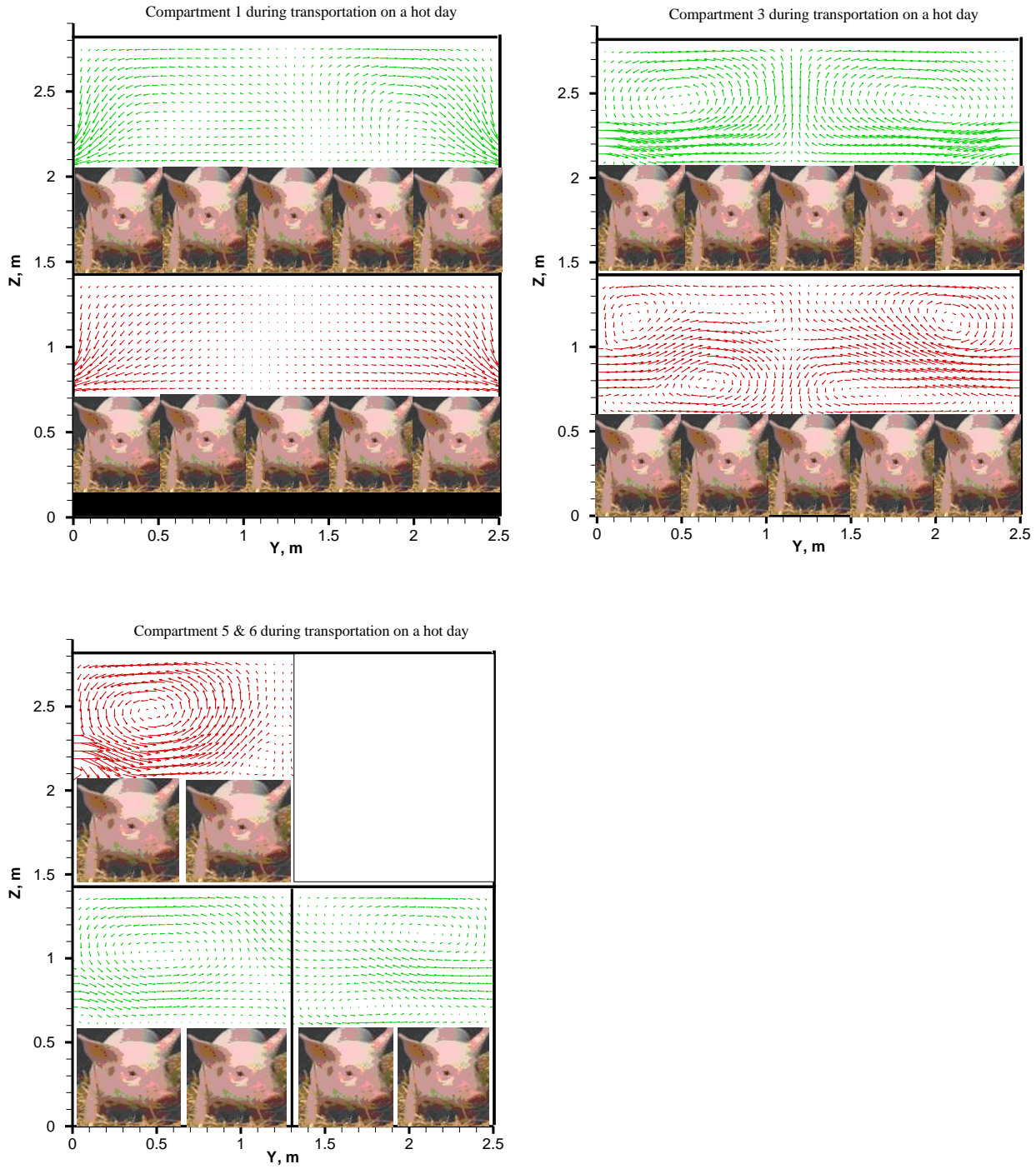


Figure 15a. Air velocity through the longitudinal section in the center of the trailer during transport on hot, mild, and cold days [Simulations 1, 6, and 11, respectively].

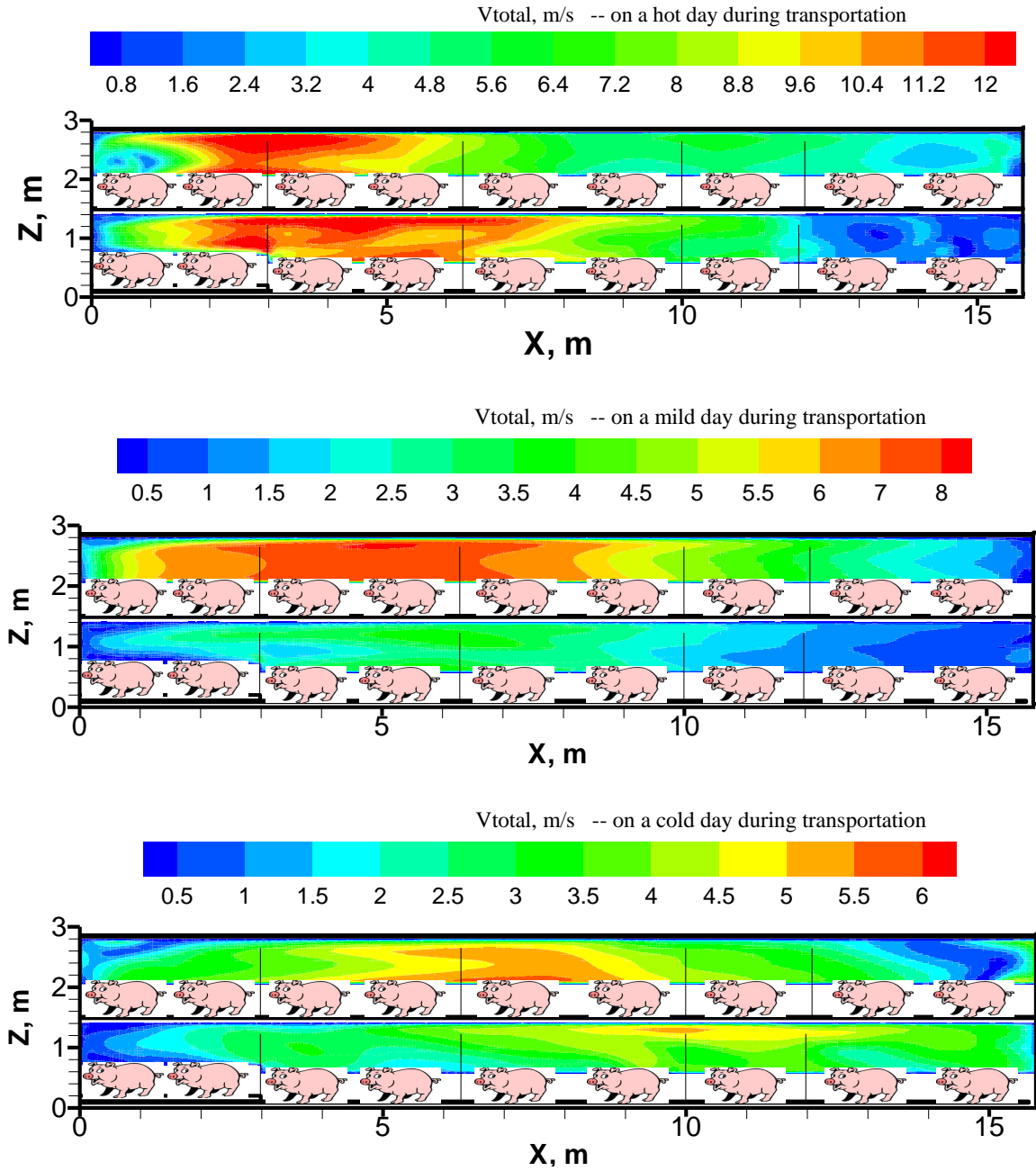


Figure 15b. Air temperature through the longitudinal section in the center of the trailer during transport on hot, mild, and cold days [Simulations 1, 6, and 11, respectively].

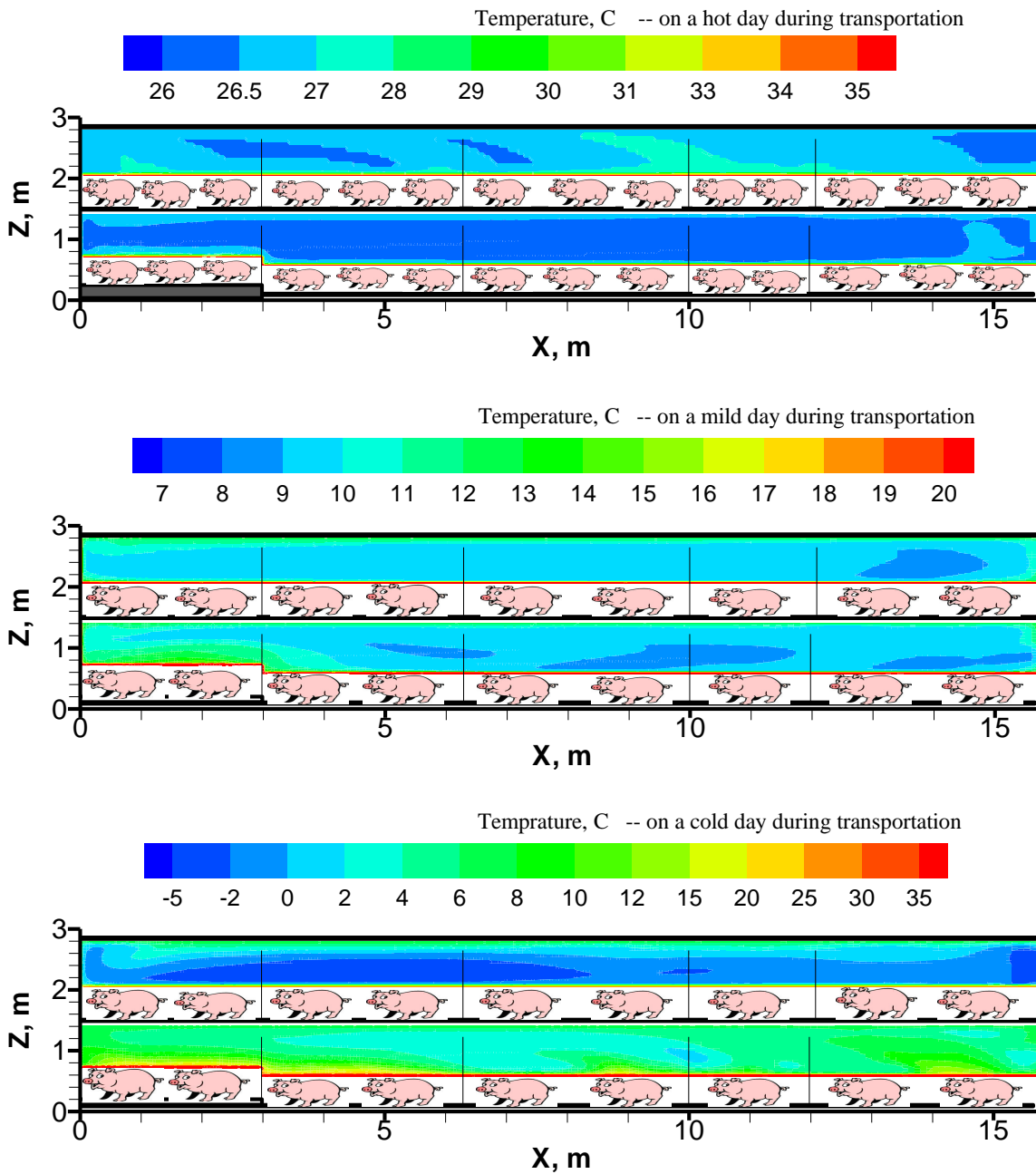


Figure 15c. Air relative humidity through the longitudinal section in the center of the trailer during transport on hot, mild, and cold days [Simulations 1, 6, and 11, respectively].

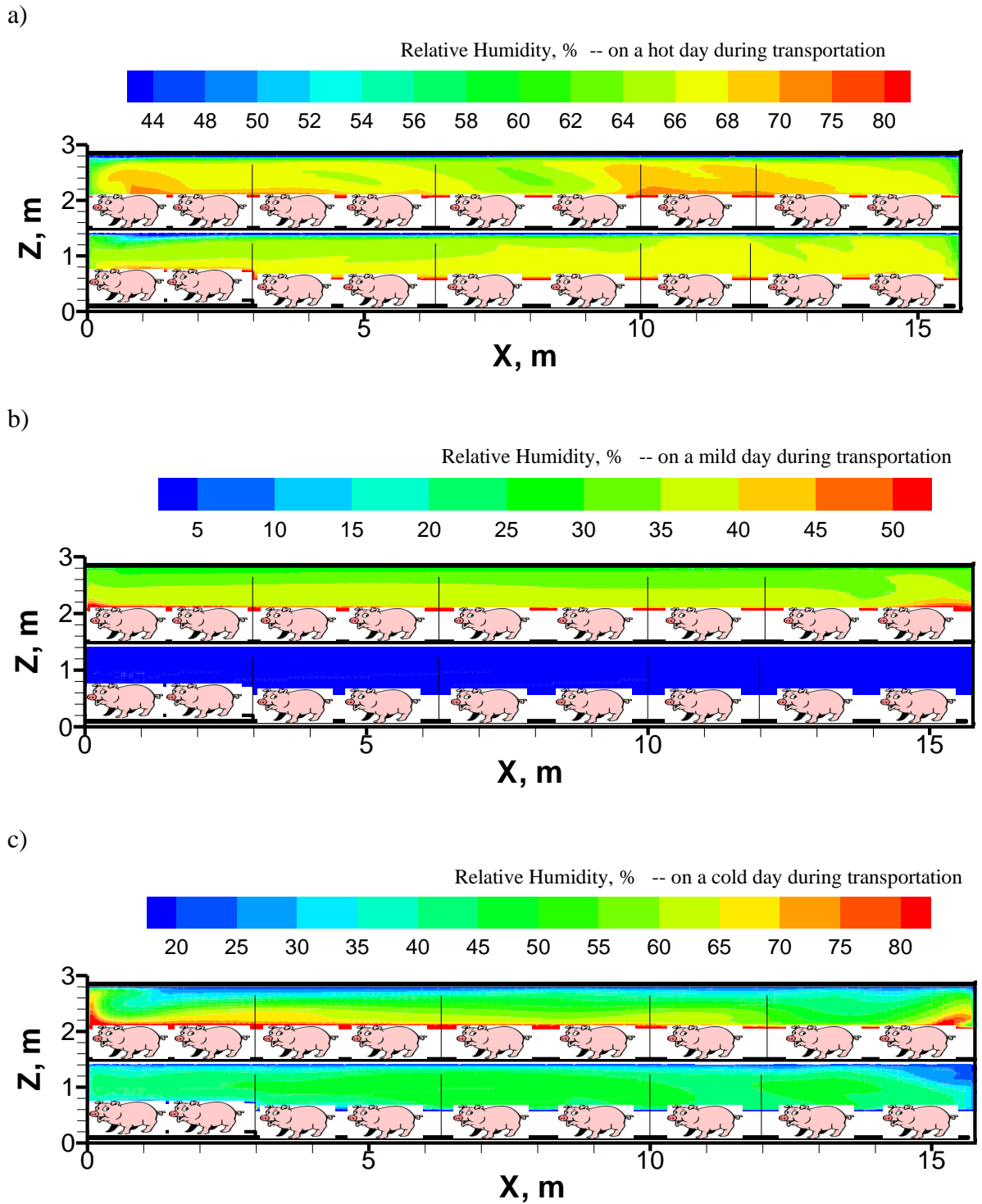


Figure 15d. Air velocity through the transverse sections of the trailer during transport on a hot day [Simulation 1].

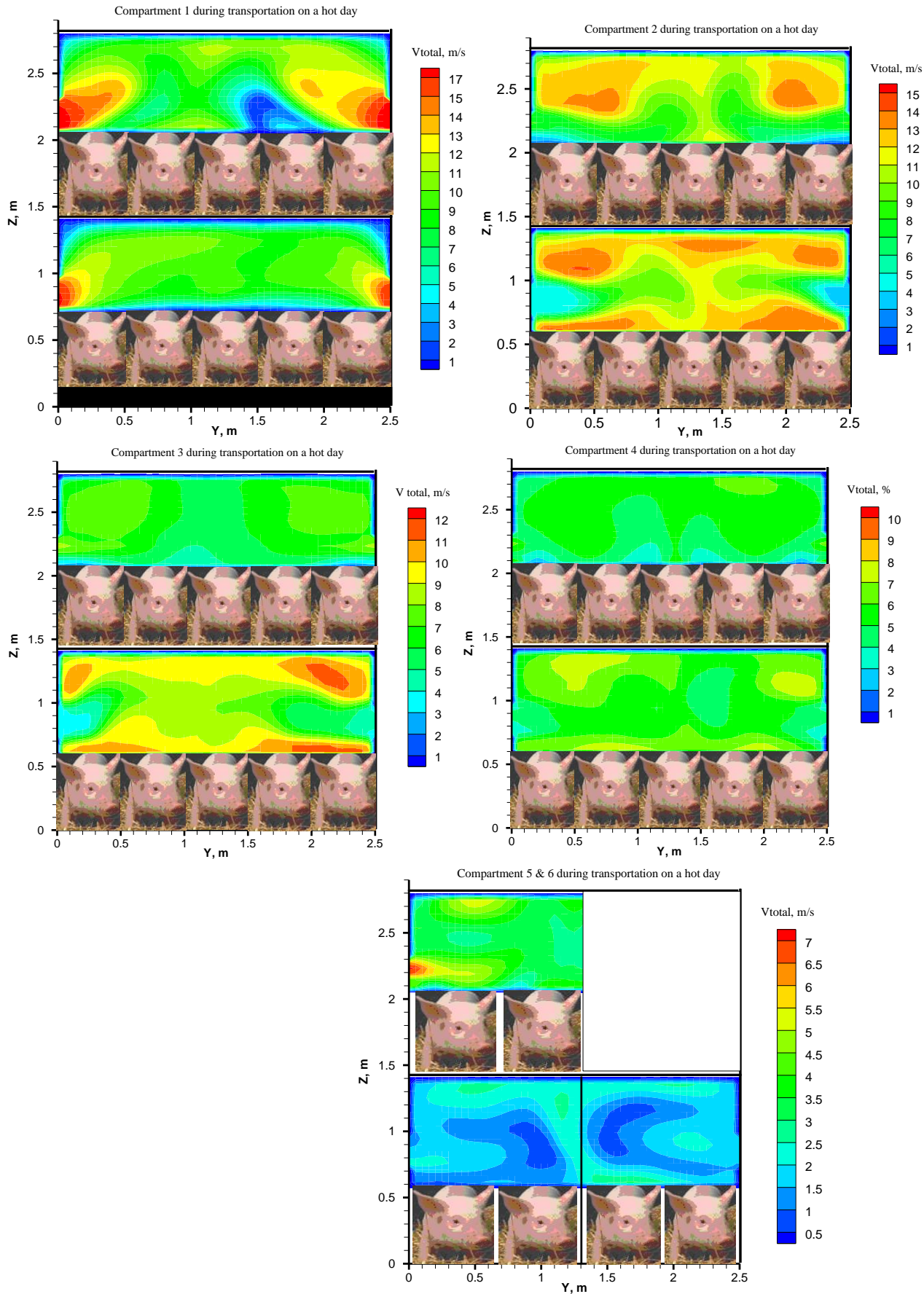


Figure 15e. Air velocity through the transverse sections of the trailer during transport on a mild day [Simulation 6].

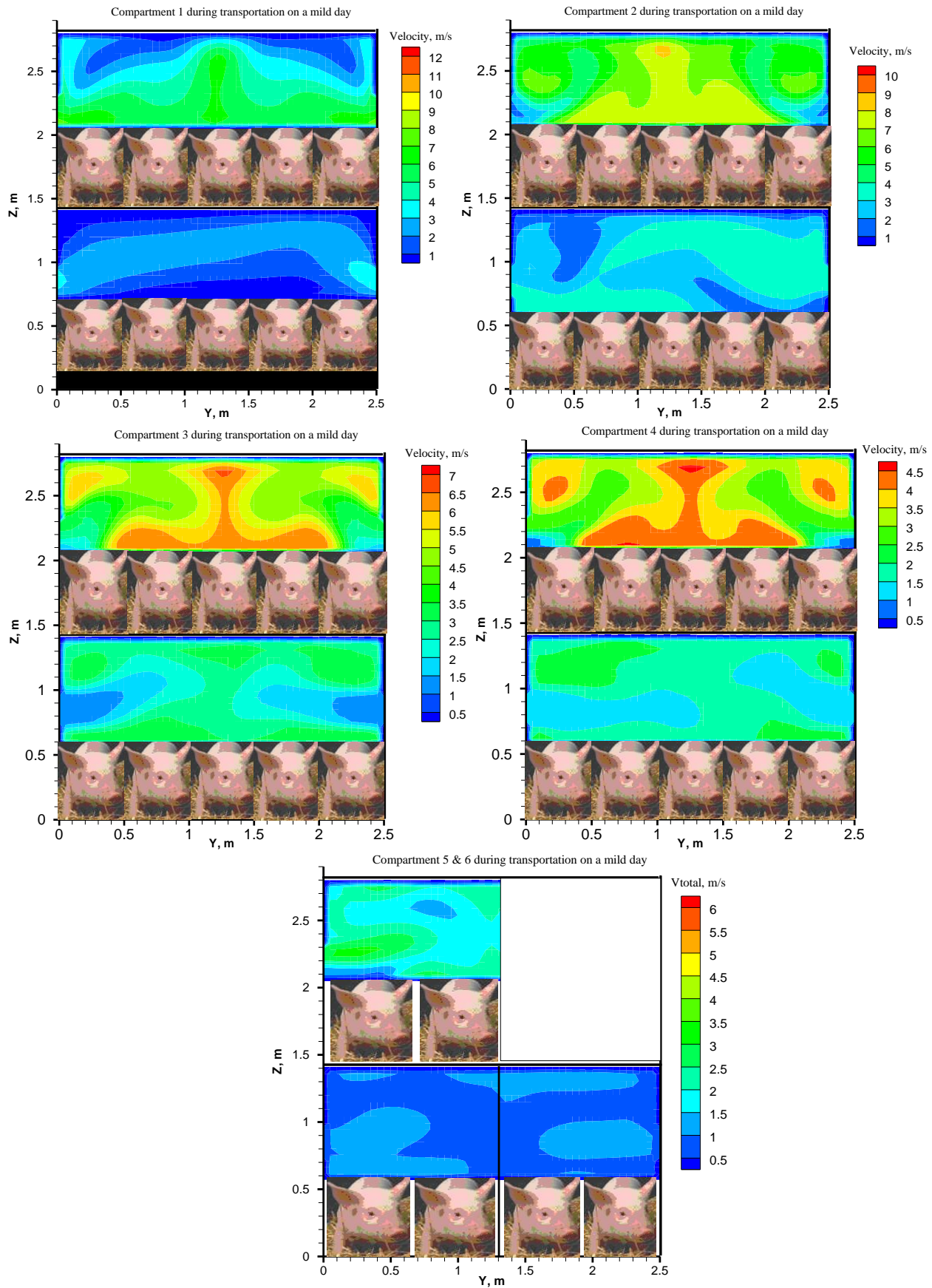


Figure 15f. Air velocity through the transverse sections of the trailer during transport on a cold day [Simulation 11].

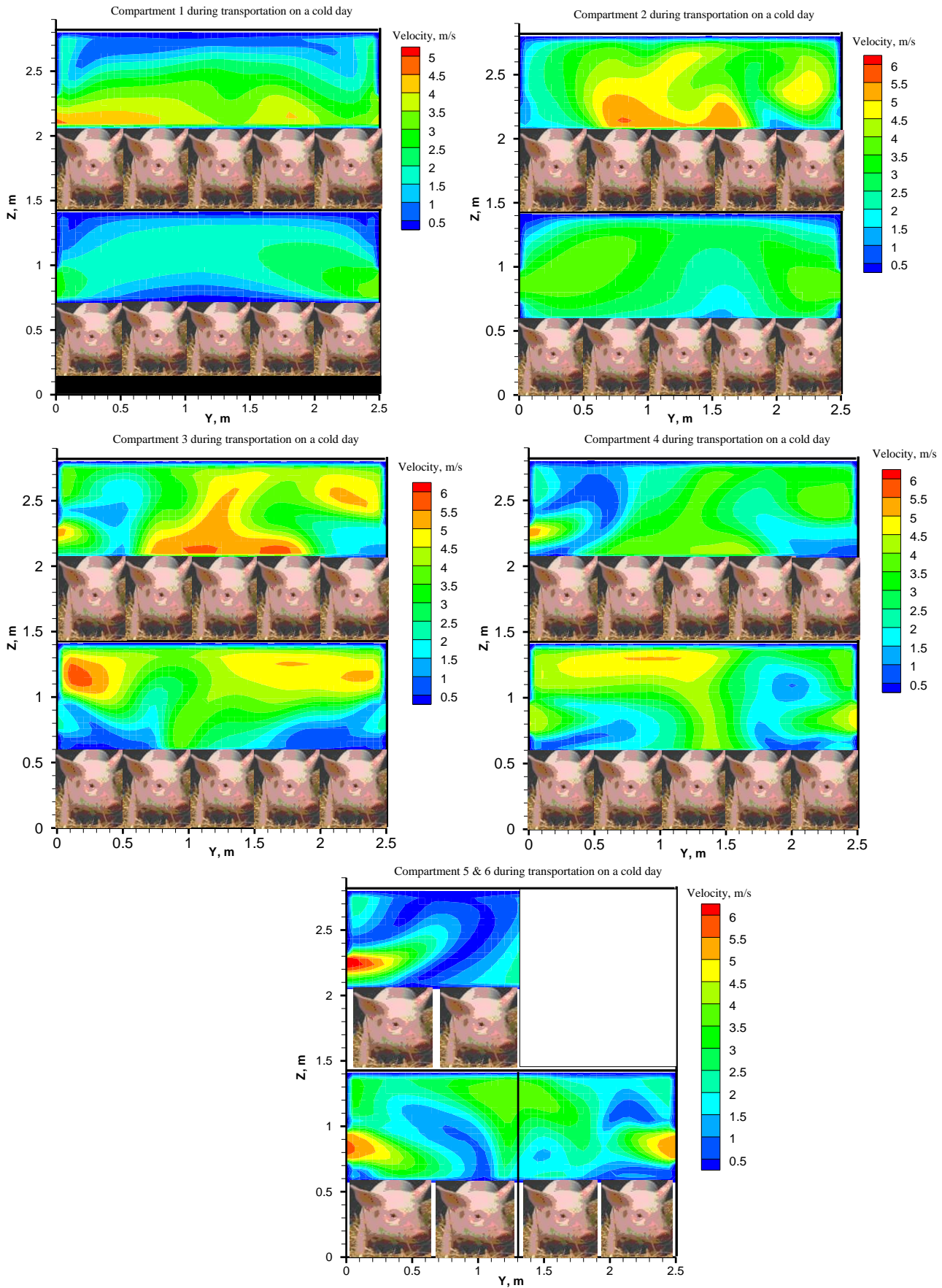


Figure 15g. Air temperature through the transverse sections of the trailer during transport on a hot day [Simulation 1].

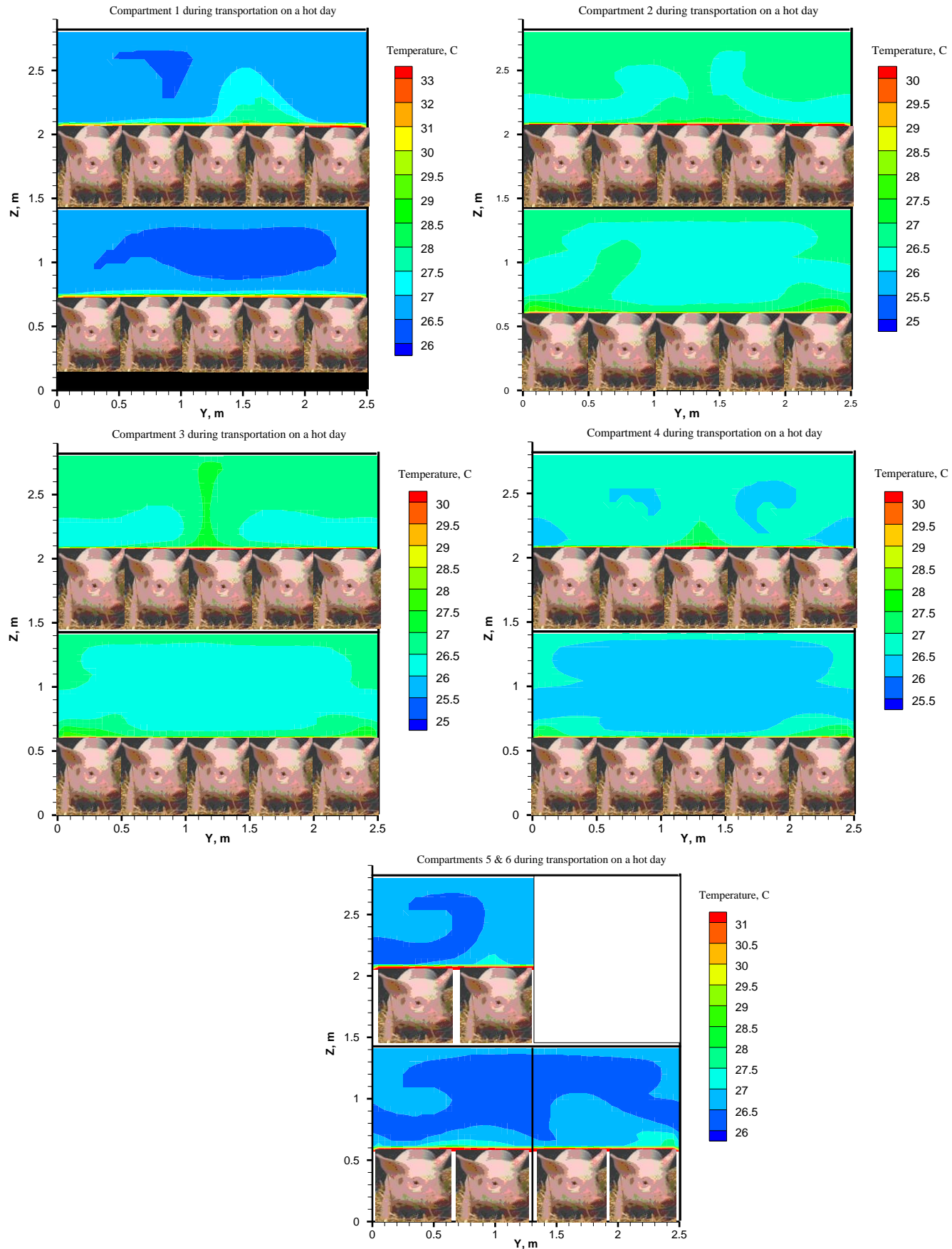


Figure 15h. Air temperature through the transverse sections of the trailer during transport on a mild day [Simulation 6].

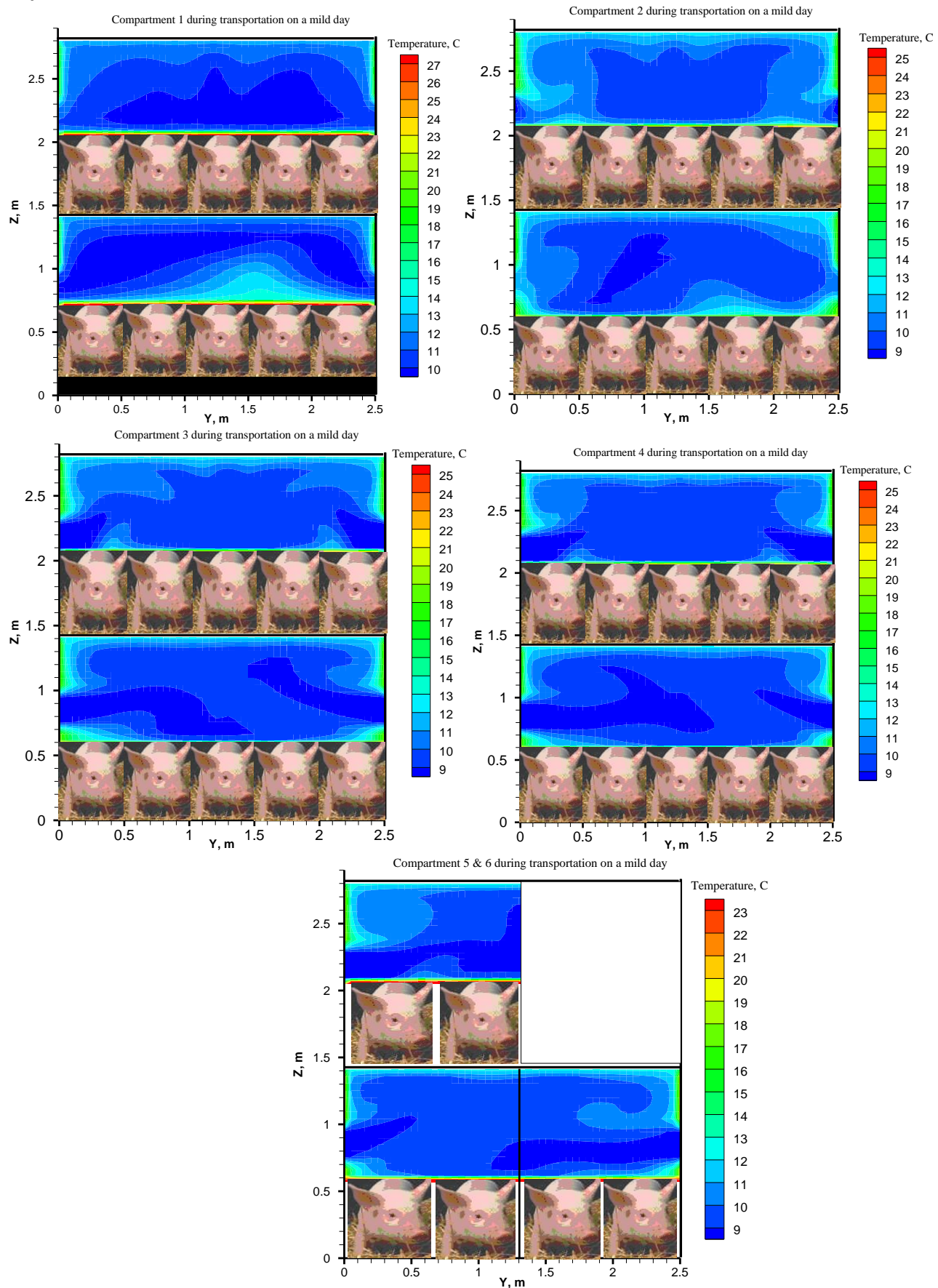


Figure 15i. Air temperature through the transverse sections of the trailer during transport on a cold day [Simulation 11].

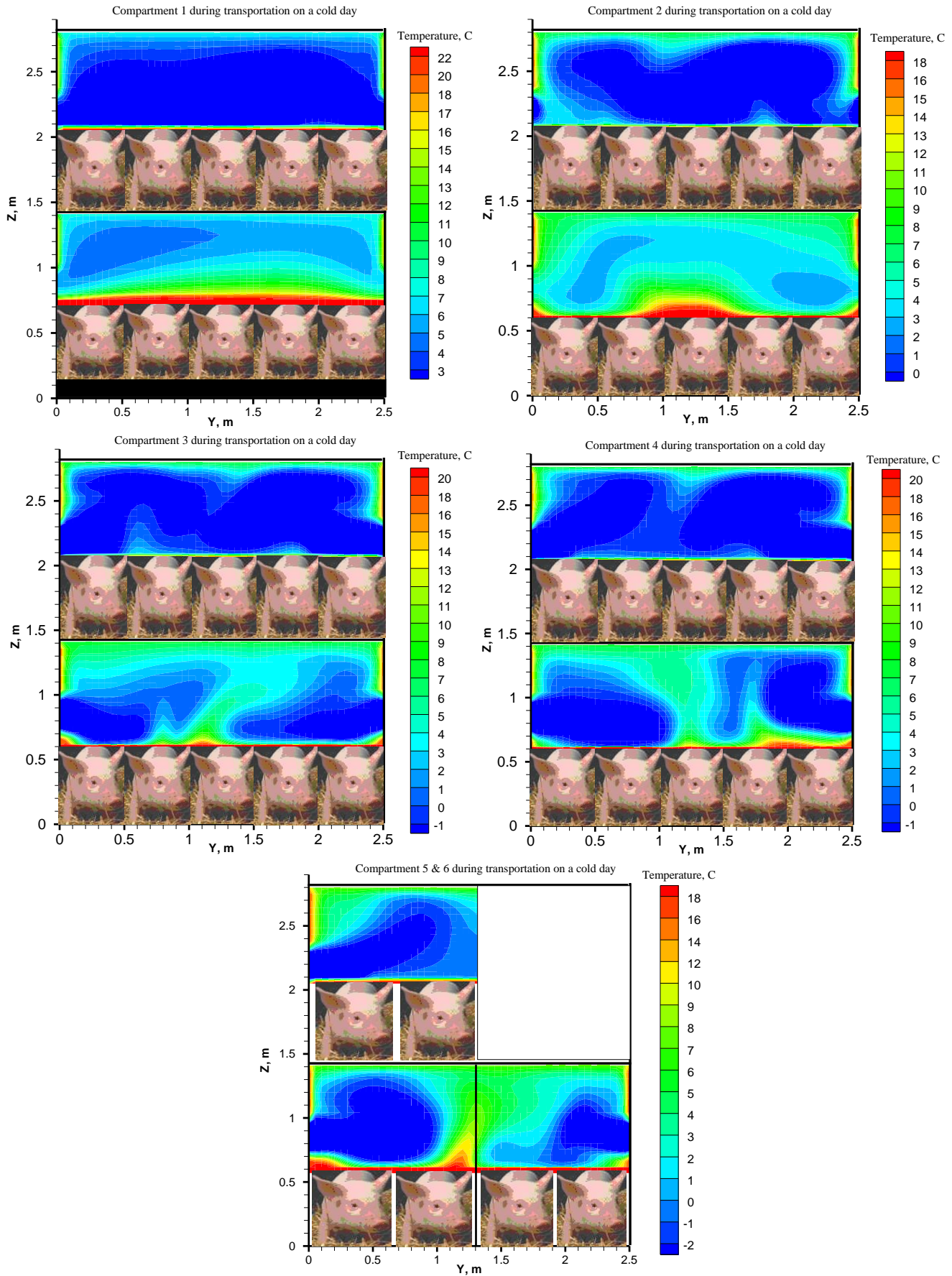


Figure 15j. Air relative humidity through the transverse sections of the trailer during transport on a hot day [Simulation 1].

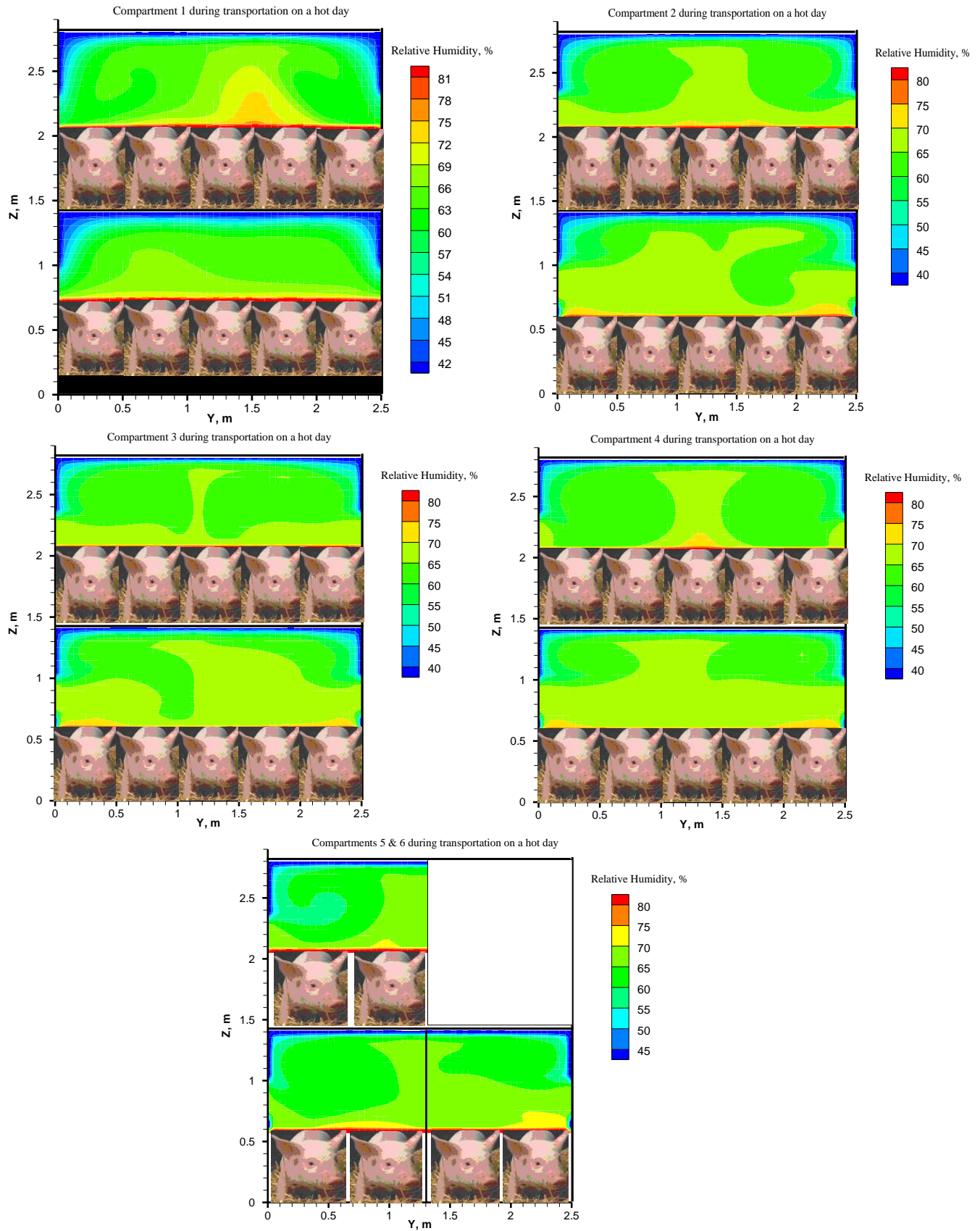


Figure 15k. Air relative humidity through the transverse sections of the trailer during transport on a mild day [Simulation 6].

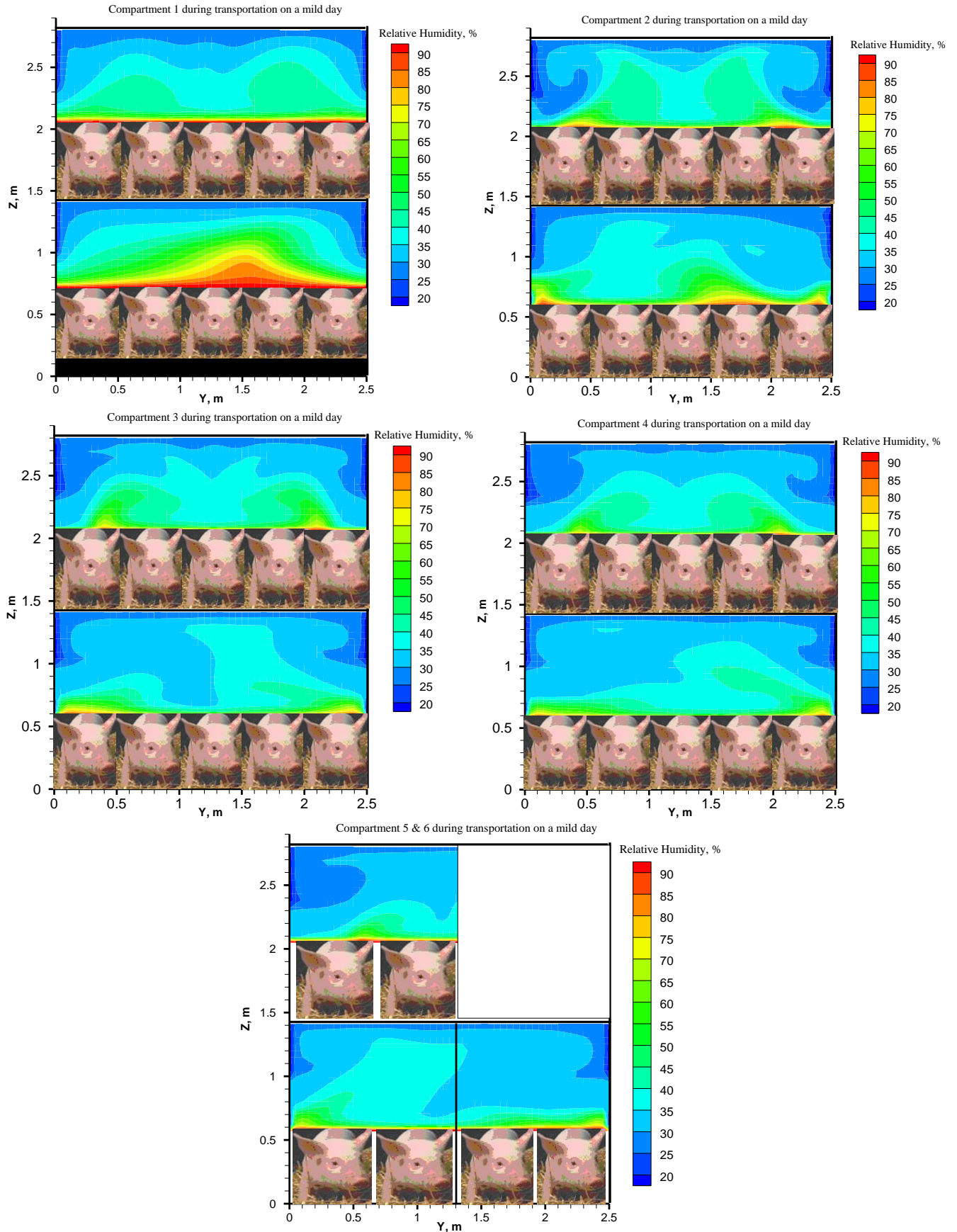


Figure 15l. Air relative humidity through the transverse sections of the trailer during transport on a cold day [Simulation 11].

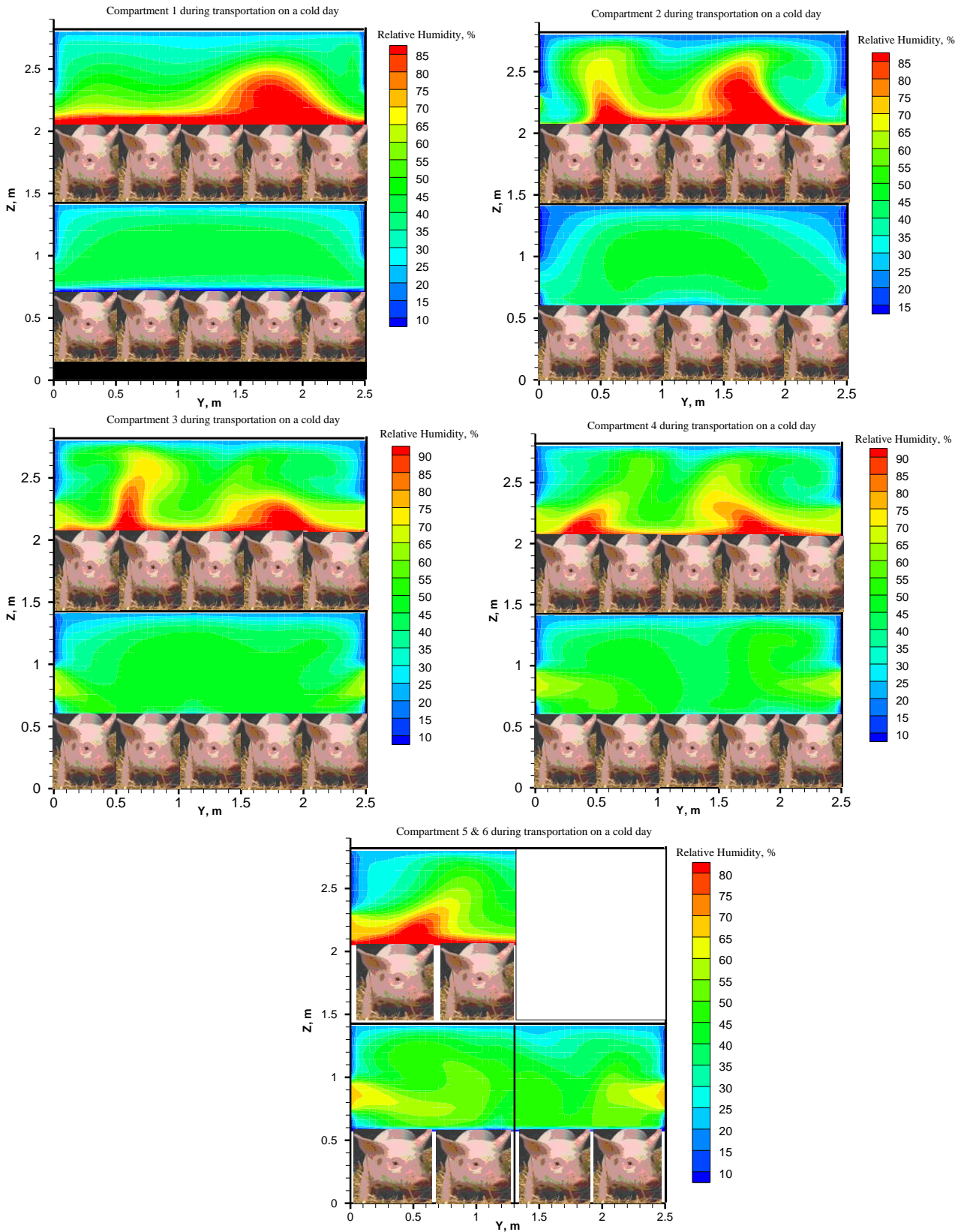


Figure 16a. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on hot, mild, and cold days – without any external fans operating. [Simulations 2, 7, and 12, respectively]

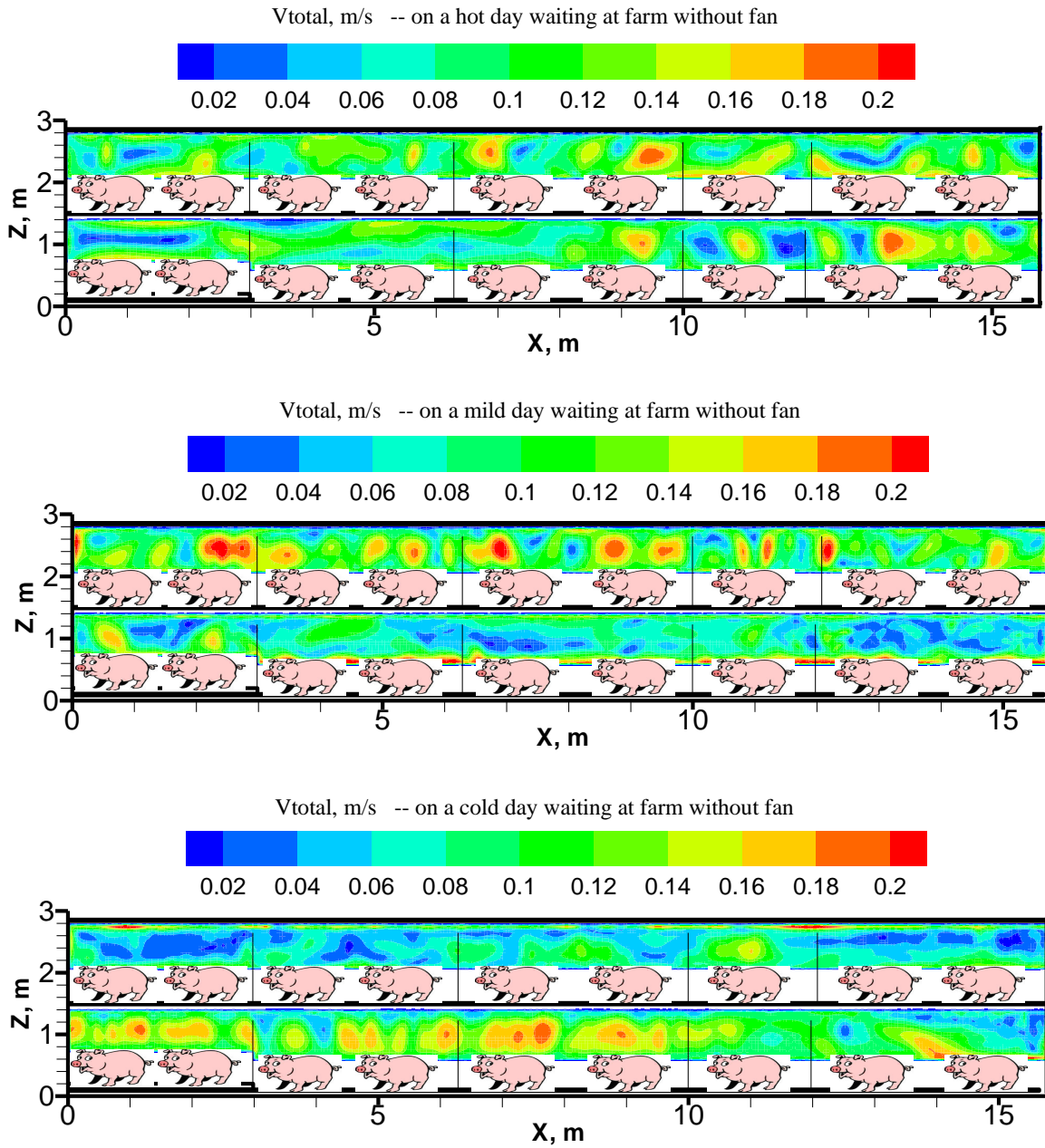


Figure 16b. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on hot, mild, and cold days – without any external fans operating [Simulations 2, 7, and 12, respectively].

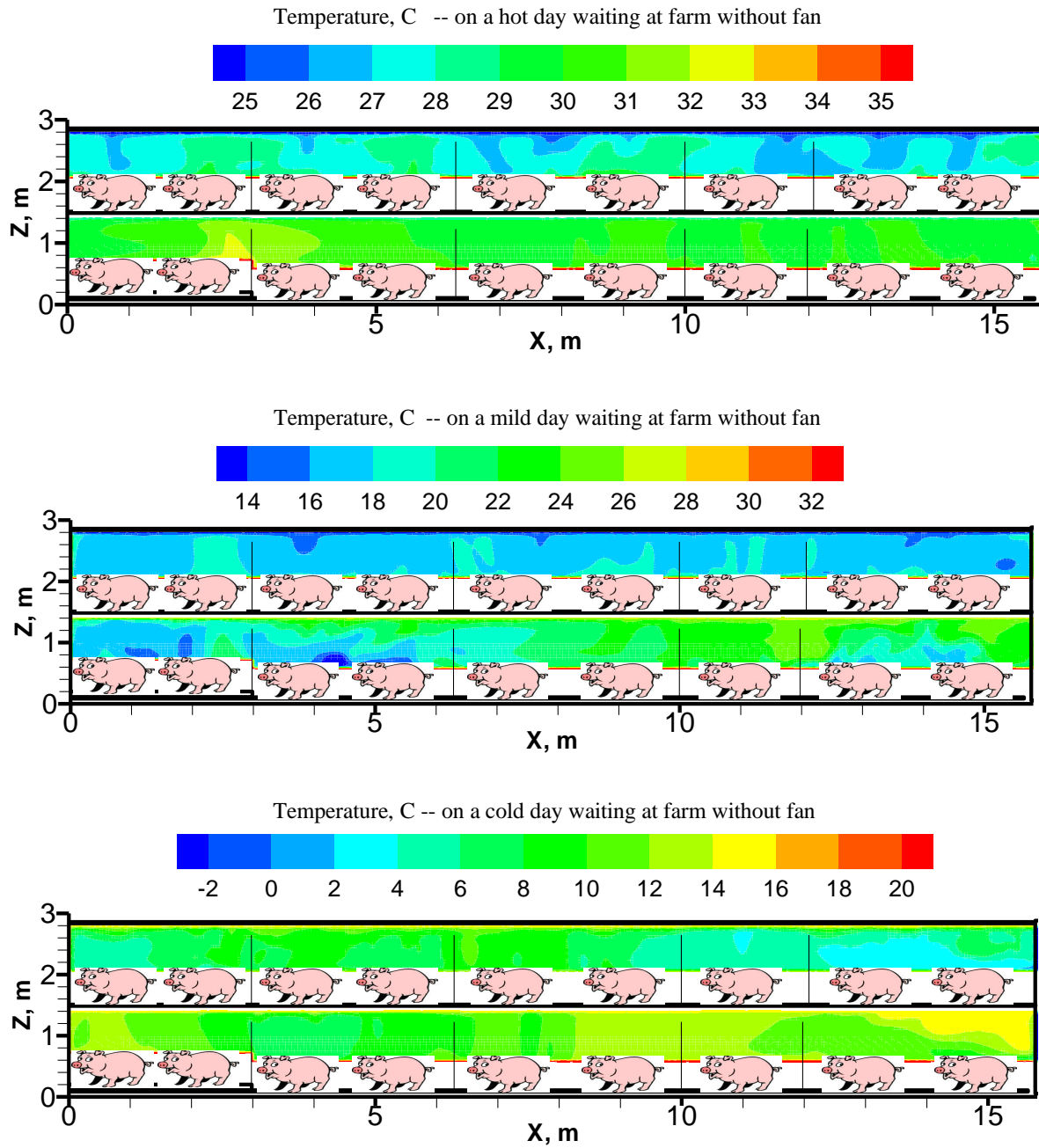


Figure 16c. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on hot, mild, and cold days – without any external fans operating [Simulations 2, 7, and 12, respectively].

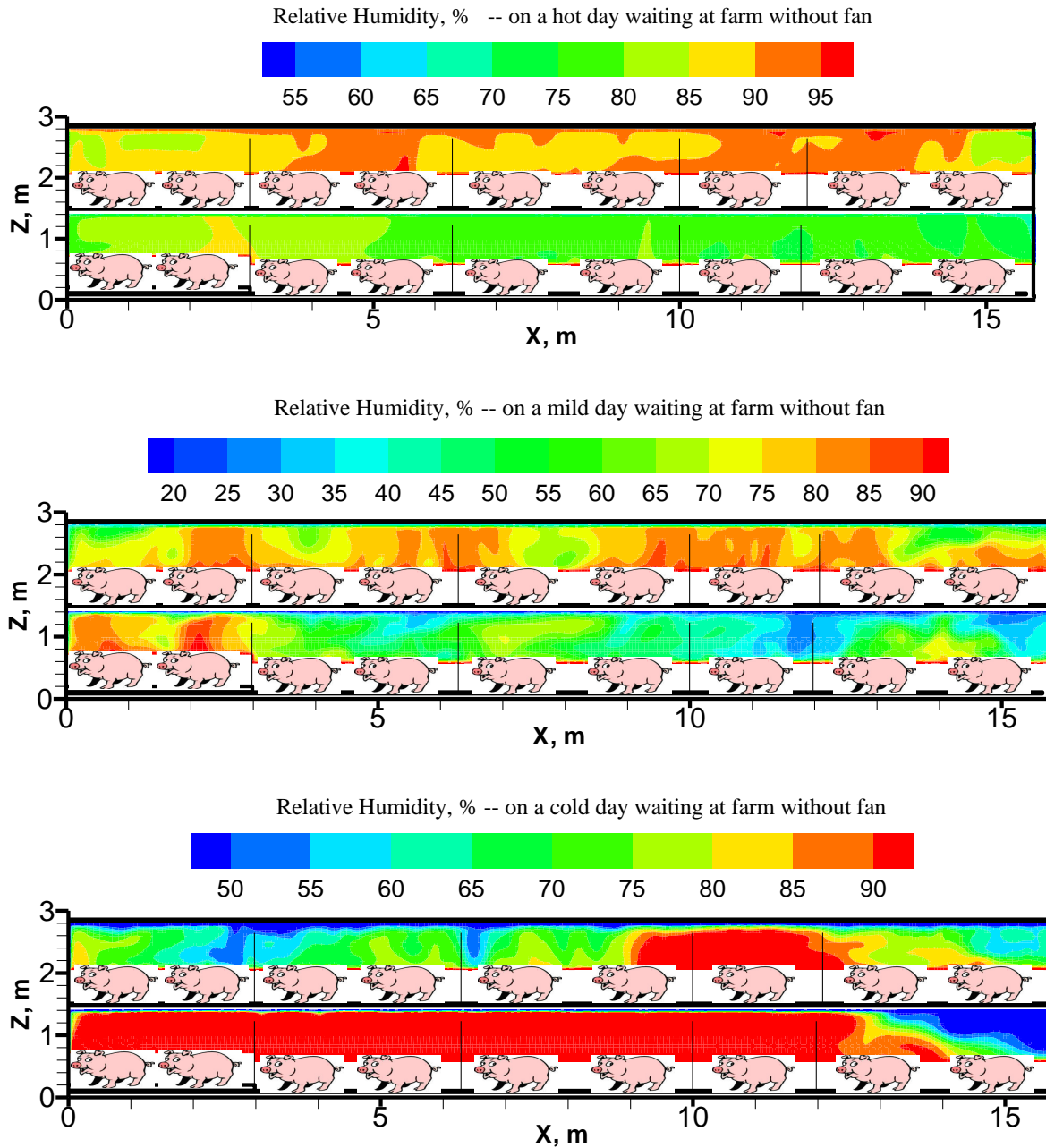


Figure 17a. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on hot, mild, and cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

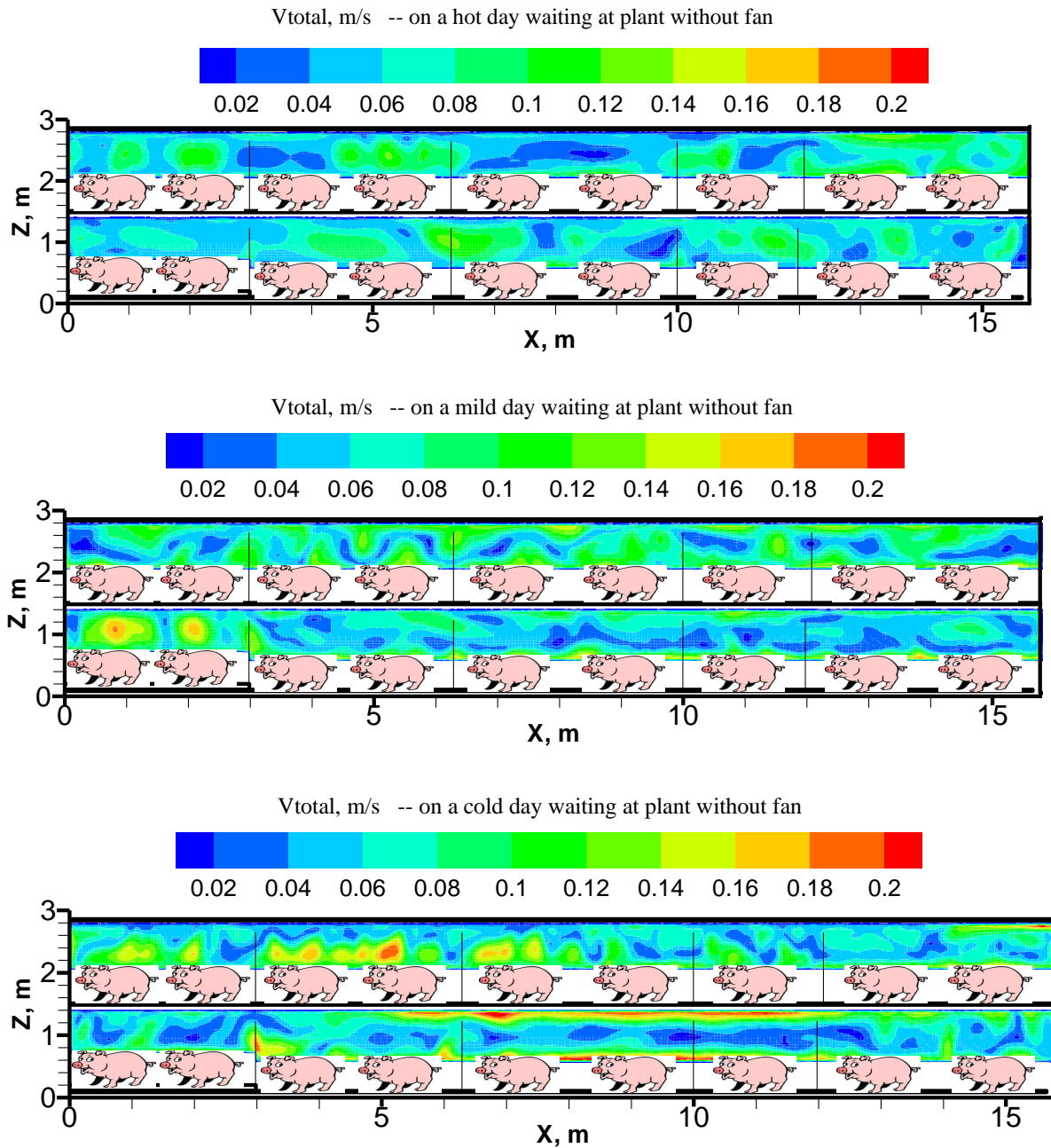


Figure 17b. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on hot, mild, and cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

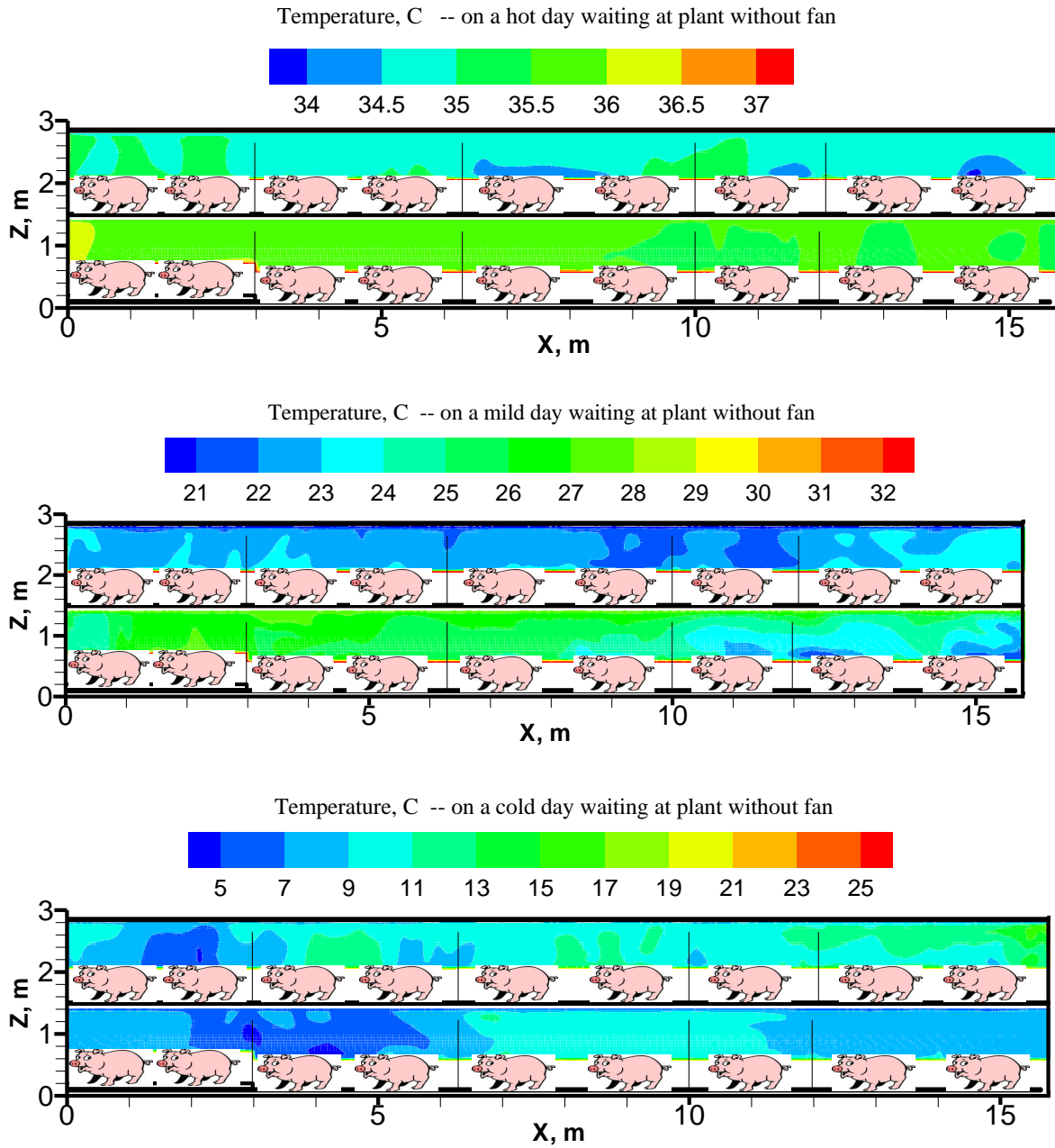


Figure 17c. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on hot, mild, and cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

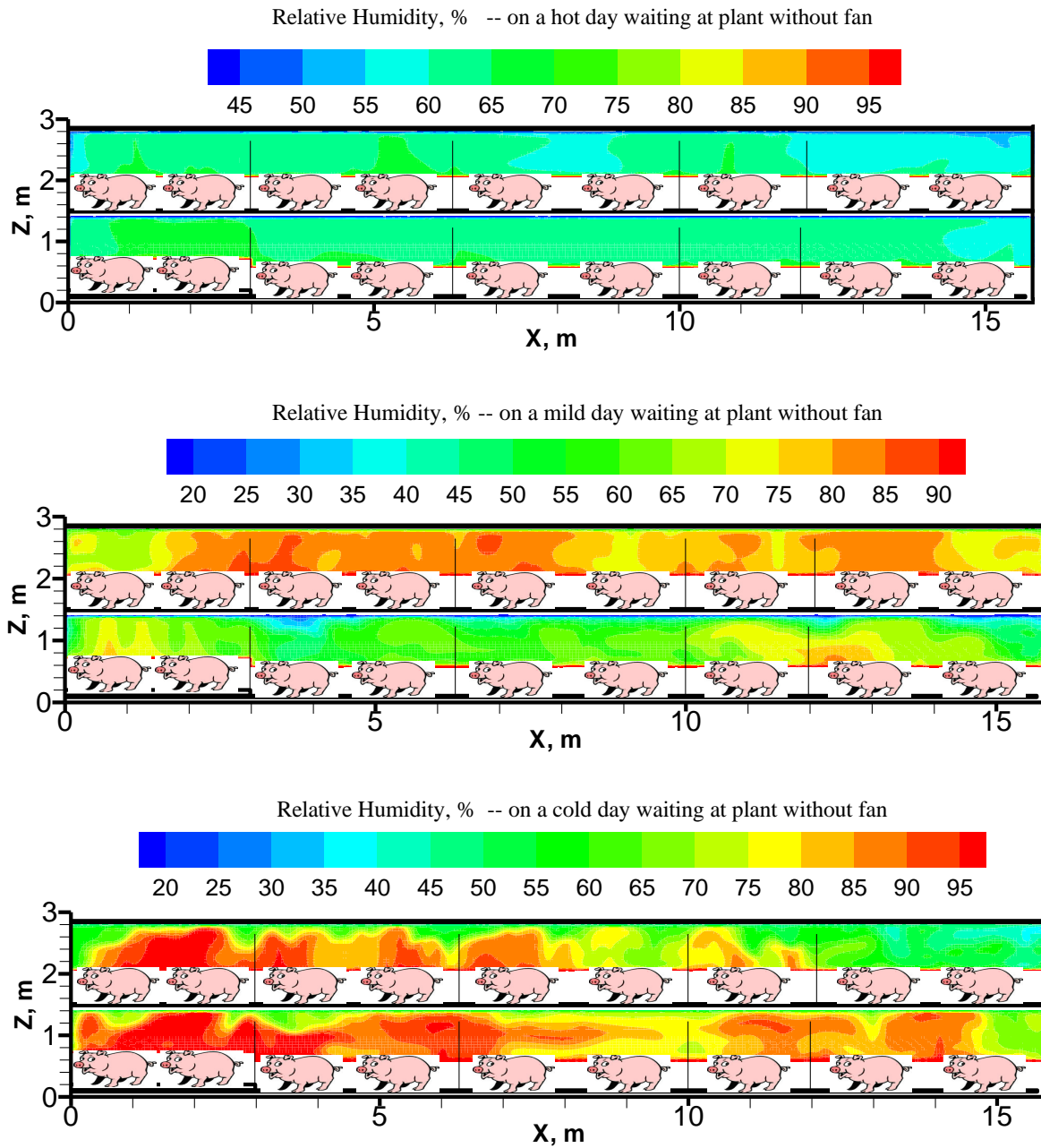


Figure 18a. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on hot, mild, and cold days – with external fans operating [Simulations 5, 10, and 15, respectively].

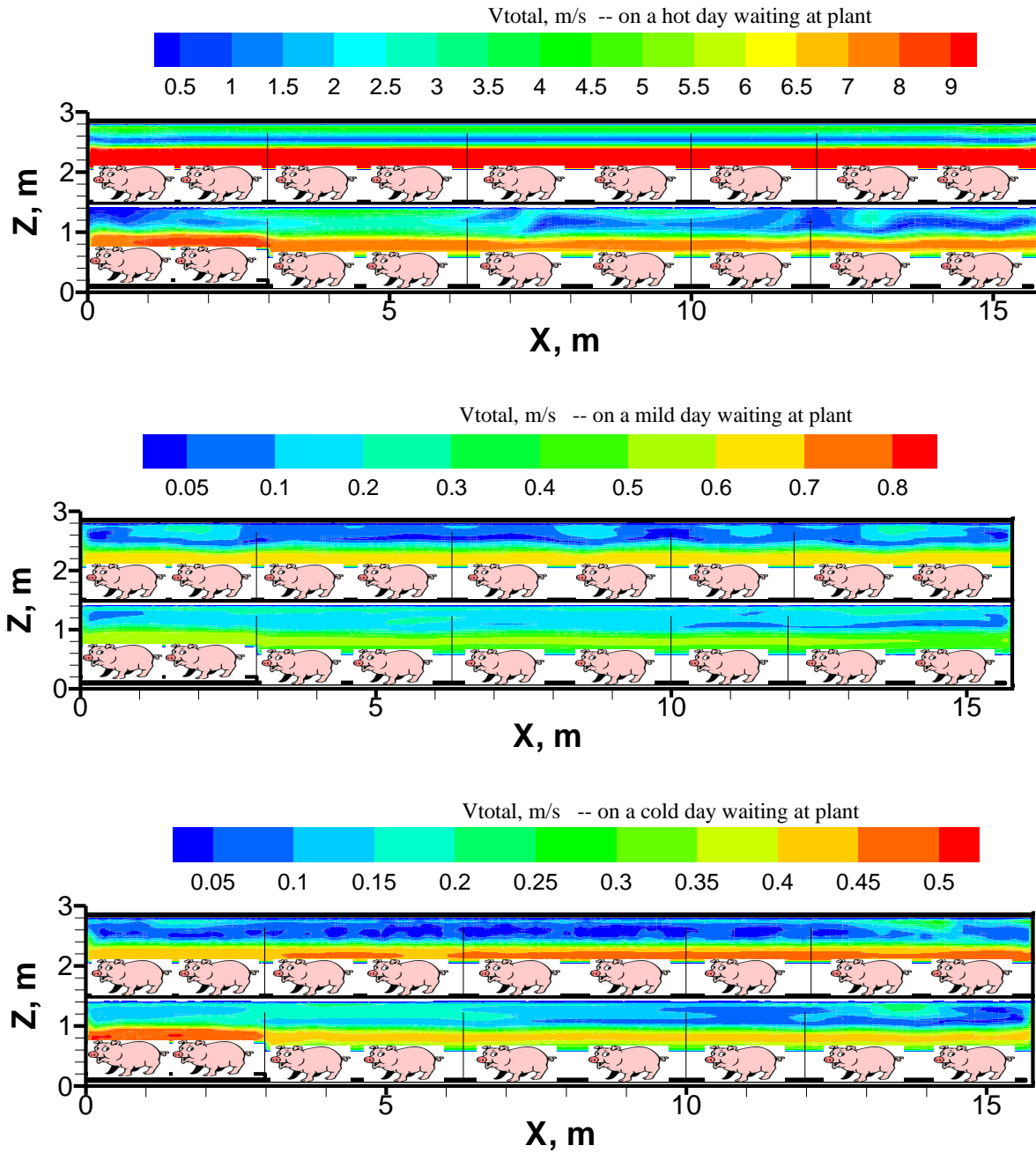


Figure 18b. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on hot, mild, and cold days – with external fans operating [Simulations 5, 10, and 15, respectively].

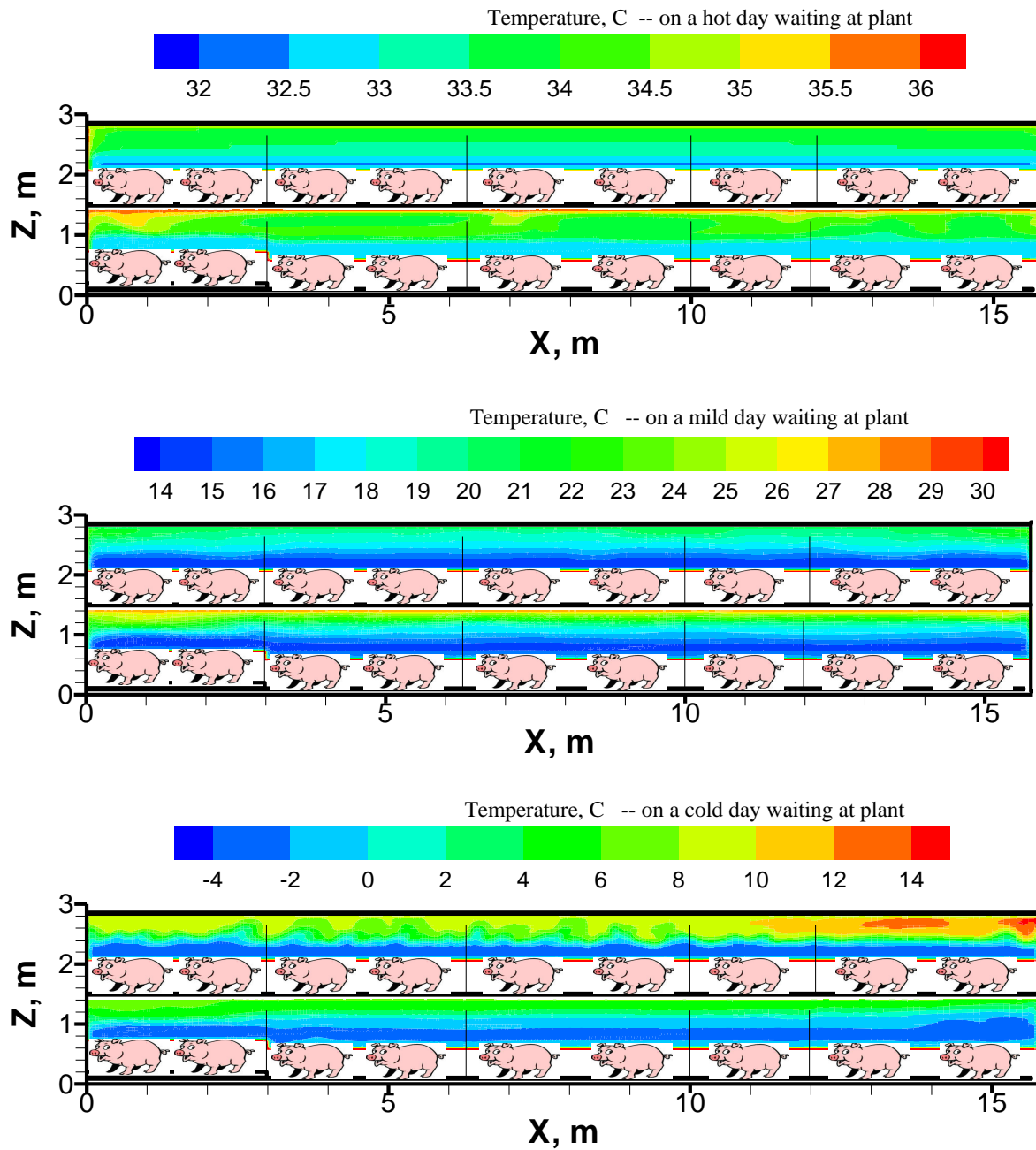
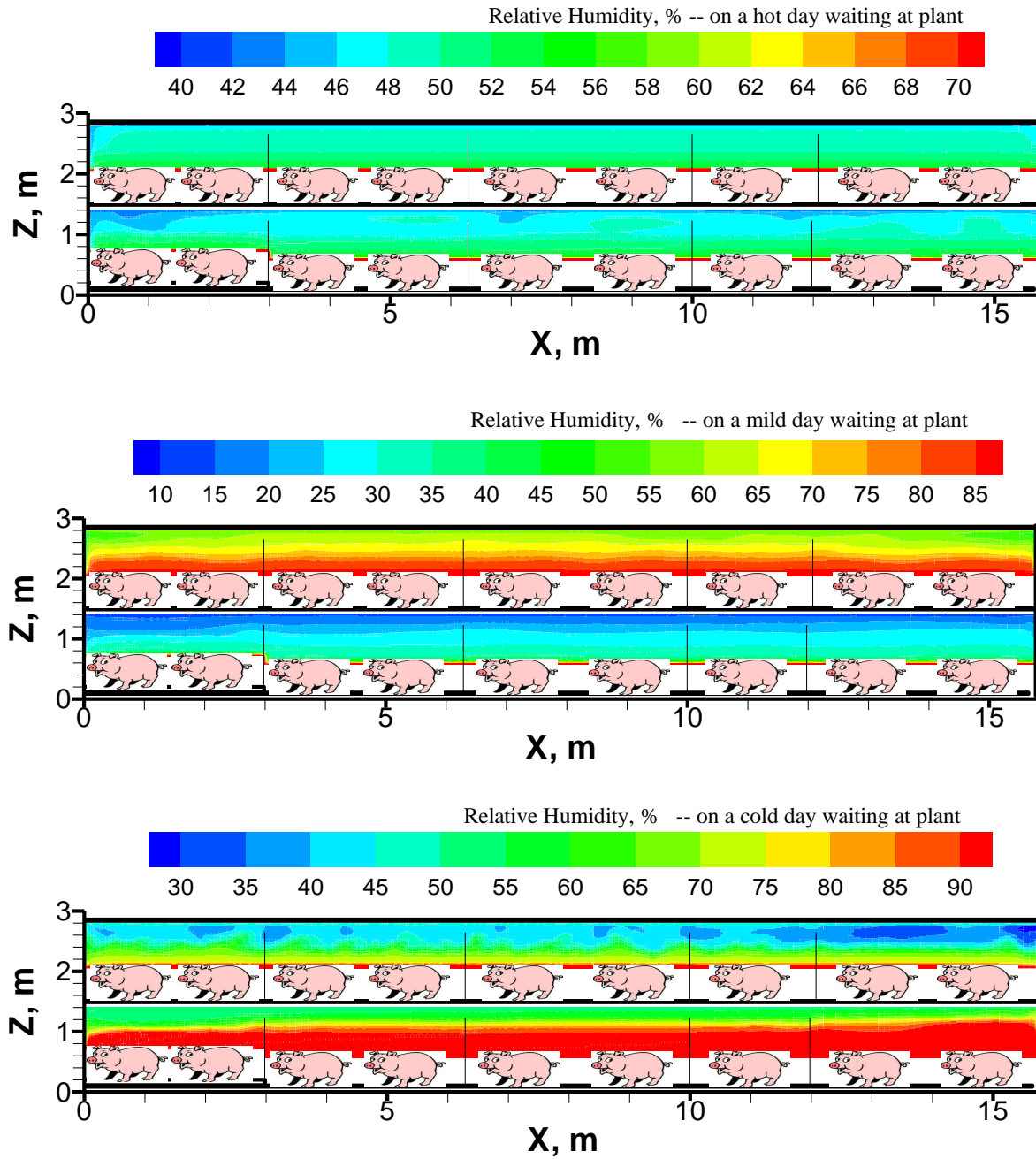


Figure 18c. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on hot, mild, and cold days – with external fans operating [Simulations 5, 10, and 15, respectively].



IX. Conclusions and Recommendations:

i. General Conclusions

- The micro-environment experienced by the pig on the trailer during transport is critical for animal well-being and, potentially, impacts both losses during the journey and pork quality.
- Historically, there has been limited research carried out monitoring the environment for pigs during transport which largely reflects the difficulty of measuring environmental parameters on the trailer during transportation.
- This project represents the first attempt, in the US at least, to develop a computer simulation model to predict the micro-environment for the finishing pig during transport from the farm to the slaughter plant.
- The project involved several phases including the development of instrumentation and data acquisition systems to collect the relevant measurements on the trailer, collection of data on environmental conditions on the trailer during transport of harvest-weight pigs from the farm to the plant under typical weather and transport conditions, analysis and interpretation of these data, construction of the model, use of model to simulate micro-environmental conditions on the trailer across the typical range of external weather conditions, and, finally, development of recommendations based on model simulations.
- The project was not without its challenges and required significant efforts from a large number of individuals with a wide range of expertise for successful completion.
- We successfully developed and tested instrumentation for measuring the range of environmental parameters that determines the heat stress on the animal (i.e., temperature, relative humidity, air velocity, surface temperatures of the inside surfaces of the trailer and of the pigs) that proved to be reliable and robust enough

to withstand the relatively challenging environment that is encountered during the transportation process. This instrumentation was used to collect measurements of environmental conditions on the trailer under the range of typical ambient conditions experienced by pigs during transportation. Measurements were taken in every compartment of the trailer at 6 second intervals. The resultant extensive data set was used to develop the computer simulation model.

- This computer simulation model predicts the micro-environment on the trailer during transport under the wide range of external weather conditions experienced in the US. In common with all other computer simulation models, a number of simplifying assumptions were made in order that a functional model could be constructed.
- Ideally, the accuracy of any model should be tested using a validation step in which data on the micro-environment on the trailer collected during transport from different loads of pigs than those used for model construction is compared with the predictions from the model. Due to constraints on time and funding, this validation step has not been carried out with the model developed in this project. However, until such validation has taken place the results from model simulations must be considered with caution.
- Results relating to the measurements taken on the trailer during the data collection phase of the project suggested the following:
 - The times of greatest extremes of and changes in temperature within the trailer were when the trailer was stationary either at the farm during loading or at the plant prior to and during unloading. These are times of low air movement within the trailer when there is the greatest potential for pigs to experience thermal stress, due to either too high or too low temperatures, and, obviously, are times when greatest care is needed to prevent problems.

- Although heat stress can be a significant problem, particularly in the summer, the data collected during the winter suggests that cold stress could also be an issue. The variation in temperature between the compartments was also greatest in the winter, suggesting, substantial localized differences in cold stress within the same trailer load of pigs.
- Temperatures were generally higher in the front compartments compared to other locations which reflects the likely direction of air flow within the trailer (from rear to front) as well as the lack of air movement in the front compartments. Increasing ventilation in the front compartments (for example, by installing a fan in the front of the trailer shell) would obviously increase ventilation rates and could reduce temperature stress under hot conditions.

ii. Recommendations for Improved Trailer Design and Management

- Given the extremes of weather that are experienced in the US, it is unlikely to be practically possible or economically feasible to design trailers for transporting pigs that provide the optimum environment on the trailer for all weather conditions. However, the data collected during this study and the model simulations based on those data highlighted the considerable variation in environmental conditions on the trailer both between seasons and, within season, between different locations on the same trailer load of pigs. The recommendations outlined here are practical approaches aimed at reducing this variation in the micro-environment for the pigs on the trailer.
- With current designs of trailer, such as the one used in this study, the openings in the side walls are identical for all compartments. Ideally, the size, shape, and position of these openings for each compartment should be varied according to the required ventilation rate, to keep the air velocity within a comfortable range for the pigs within all compartments.

- Results of simulations showed that CO₂ concentrations varied along the trailer and were considerably higher towards the front. This suggests that ventilation rates were lower towards the front than towards the rear of the trailer. To overcome this problem, the ventilating holes in the side walls of the front compartments should be larger than those in the rear of the trailer. In this manner, the air movement in the front would be more consistent with the air movements in the other compartments.
- On current trailer designs, the number of the side-wall slats open or closed can only be adjusted independently from the front to back of the trailer using slats, however, it is not possible to vary the number of slats open or closed between the top and the bottom decks. Having this capability would allow for separate ventilation of the two decks of the trailer and, therefore, should provide more optimal conditions on the two decks. A guideline for installing the side slats is needed; however, to develop such a guideline will require further model development with more detailed and accurate geometrical modeling of the side openings and the impact of opening or closing these with slats.
- An automatic system for changing sidewall openings based on external conditions would be the ideal and should be explored. Conditions change so drastically and quickly, from loading at the farm to travel on the road, to the period of waiting at the plant, such that it is unreasonable to assume that one set of ventilation openings can handle all situations and still maintain pig comfort.
- The sidewall openings on the trailer design used in this study were inadequate for hot weather, particularly when the truck was parked. Manufacturers need to explore ways to increase sidewall openings, and these openings need to be combined with an automatic system to change the size of the openings. Results of the simulations indicate that the ventilation openings should probably be managed as three independent systems, namely, the front two compartments on both decks

(Compartments 1 and 2), the center two compartments on both decks (3 and 4), and the rear compartments on both decks (5 and 6).

- The use of the external fans at the plant to cool the pigs proved not to be very efficient at increasing the ventilation rate in the trailer and eliminating the heat stress on the pigs. It is strongly recommended that fans be installed in the front end-wall to blow air backward along the trailer. Installation of one large A/C fan, powered via extension cord at the farm during loading and at the plant during waiting, in the front end-wall of the trailer on each deck (two fans total; one upper, one lower) will provide some airflow in summer. The fans could be covered and/or removed for winter. Mounting the fans in the end-wall would reduce the interference with the loading and unloading processes, and would keep the fans out of the reach of the pigs.

- Dry bedding is important in cold weather, and wetted bedding could be useful in summer for improving heat transfer via evaporation. The physical characteristics, especially the heat transfer characteristics, of the bedding material need to be established for this to be included in the simulation model to identify the most appropriate type and amount of material to use with different environmental conditions.

iii. Recommendations for Future Data Collection

- Collecting data in a moving livestock trailer is a difficult task. Past experience is limited and mistakes can be easily made. Although a majority of the equipment in this study worked extremely well, several modifications can be made to improve the data collection process as follows:
 - Use of water-resistant sensors
The trailer sprinkling system was not used during testing in order to prevent damage to the equipment. Water-resistant sensors can examine the effect of sprinkling of the pigs on heat stress.

- Re-design of attachment for the sensor packs
A quicker attachment will save time when removing and installing the sensors in the trailer.
- Self-cleaning infrared sensors
Dust often collected on the sensing head for the infrared temperature sensors. An air purge system can help keep the sensing lens clean while still providing accurate results.
- Improved carbon dioxide sensors
A more robust CO₂ sensor may provide more accurate measurements and will not be affected as much by high relative humidity levels or dusty conditions.
- Modify the data acquisition system
The recording hardware and/or the software program caused problems with shutting down during testing. Finding a more optimal combination will help ensure full data collection. Data loggers designed for use with automotives may be more reliable and should be considered.

iv. Recommendations for Future Research

There are a large number of factors that influence the micro-environment experienced by pigs on the trailer during transport. Additionally, ventilation in a trailer has always been difficult to describe and even more difficult to measure. Results from this research have suggested several areas in need of further study to provide a better understanding of the micro-environment experienced by the pigs during transport.

- Take measurements at several locations in each compartment.
This can help determine heat and air flow within a compartment, which can in turn lead to the development of more accurate models.
- Use video cameras in conjunction with sensors.
Cameras can be used to monitor the activity levels of the pigs and help determine the link between pig behavior and aspects such as heat and carbon dioxide production.
- Use more advanced air velocity sensors.

Determining the direction of air movement will aid in understanding air flow patterns on the trailer.

- Use different pig stocking densities on the trailer.

The influence of the number and weight of pigs on environmental conditions on the trailer should be determined.

- Use of a tracer gas.

Using a tracer gas and measuring decay rates will allow ventilation rates to be accurately determined for the entire trailer or for individual compartment.

v. Recommendations for Future Model Development

The next steps in the development of the model would be to:

- Improve the model to include new information on bedding characteristics, turbulence intensity, and ambient conditions.
- Implement the improved model while allowing the trailer ventilation openings to vary at the front, center, and/or rear of the trailer to equalize the conditions inside the compartments.
- Use the simulations to determine the optimum (based on balance of pig comfort and economic considerations) number, type, and deployment of sensors within the trailer and external to it. Best-case results would indicate that the most rugged and lowest cost sensor system would provide all the inputs necessary for control in all weather conditions and all parts of the journey.
- Create more accurate and detailed geometric models of the trailer of current and improved design.
- Collect the heat transfer parameters of the material of the trailer, bedding, and pigs by measurements and survey.
- Develop a more accurate mathematical description of the ambient conditions on the trailer during transportation, such as the relative wind speed, direction, turbulence intensity, humidity, temperature, and road conditions.
- Combine Computational Fluid Dynamics with zonal modeling methodology to obtain reliable results with less computer power requirements.

X. References

- Anderson, D.B., D.J. Ivers, M.E. Benjamin, H.W. Gonyou, D.J. Jones, K.D. Miller, R.K. McGuffey, T.A. Armstrong, D.H. Mowrey, L.F. Richardson, R. Seneriz, J.R. Wagner, L.E. Watkins, and A.G. Zimmerman. 2002. Physiological responses of market hogs to different handling practices. Pages 399-400 in Proceedings of the American Association of Swine Veterinarians, Kansas City, MO.
- Baker, C. J., S. Dalley, X. Yang, P. Kettlewell, and R. Hoxey. 1996. An Investigation of the Aerodynamic and Ventilation Characteristics of Poultry Transport Vehicles: Part 2, Wind Tunnel Experiments. *Journal of Agricultural Engineering Research* 65(2): 97-113.
- Benjamin, M.E., H.W. Gonyou, D.J. Ivers, L.F. Richardson, D.J. Jones, J.R. Wagner, R. Seneriz and D.B. Anderson. 2001. Effect of animal handling method on the incidence of stress responses to market swine in a model system. *Journal of Animal Science* (Suppl 1):279. (Abstr).
- Christensen, L. and P. Barton Gade. 1995. Design of experimental vehicle for transport of pigs and some preliminary results of environmental measurements. New information on welfare and meat quality of pigs as related to handling, transport and lairage conditions. Proceedings of the SV-Seminar. Pages 47-68.
- Hamilton, D. N., M. Ellis, G. E. Bressner, B. F. Wolter, D. J. Jones and L. E. Watkins. 2003. Relationships between Environmental Conditions on Trucks and Losses During Transport to Slaughter in Finishing Pigs. *Journal of Animal Science* 81(suppl.2)(52(Abstr)).
- Hoxey, R. P., P. J. Kettlewell, A. M. Meehan, C. J. Baker, and X. Yang. 1996. An Investigation of the Aerodynamic and Ventilation Characteristics of Poultry Transport Vehicles: Part I, Full-scale Measurements. *Journal of Agricultural Engineering Research* 65(1): 77-83.
- Kettlewell, P. J., R. P. Hoxey, R. L. Hartshorn, I. R. Meeks, and P. Twydell. 2001a. Controlled Ventilation System for Livestock Transport Vehicles. In *Livestock Environment VI: Proceedings of the 6th International Symposium*, 556. St. Joseph MI: ASABE.
- Kettlewell, P. J., C. J. Hampson, N. R. Green, N. J. Teer, and B. M. Veale. 2001b. Heat and Moisture Generation of Livestock During Transportation. In *Livestock Environment VI: Proceedings of the 6th International Symposium*, 519. St. Joseph MI: ASABE.
- Lambooy, E. 1988. Road Transport of Pigs Over a Long Distance: Some aspects of behaviour, temperature and humidity during transport and some effects of the last two factors. *Animal Production* 46:257.
- Lewis, C. R. G. 2006. Transportation and Handling of Swine in Commercial Operations. Lubbock, TX: M.S. Thesis, Department of Animal Science, Texas Tech University.
- Mitchell, M. A., and P. J. Kettlewell. 1998. Physiological stress and the welfare of broiler chickens in transit. Solutions not problems. *Poultry Science* 77:1803-1814.

- National Pork Board. 2004. Trucker Quality Assurance Handbook. 21-26.
- Ritter, M.J., M. Ellis, J. Brinkmann, J.M. DeDecker, K.K. Keffaber, M.E. Kocher, B.A. Peterson, J.M. Schlipf, and B.F. Wolter 2006. Effect of floor space during transport of market weight pigs on the incidence of transport losses at the packing plant and the relationships between transport conditions and losses. *Journal of Animal Sciences* 84:2856-2864..
- Ritter, M. J., M. Ellis, J. Brinkmann, J. M. DeDecker, K. K. Keffaber, M. E. Kocher, B. A. Peterson, J. M. Schlipf, and B. F. Wolter. 2006. Effect of Floor Space during Transport of Market-Weight Pigs on the Incidence of Transport Losses at the Packing Plant and the Relationships between Transport Conditions and Losses. *Journal of Animal Science* 84(10): 2856-2864.
- SAS. 1990. *SAS User's Guide: Statistics*. Ver. 6a. Cary, NC: SAS Institute, Inc.
- Stull, C. L. 1999. Responses of Horses to Trailer Design, Duration, and Floor Area during Commercial Transportation to Slaughter. *Journal of Animal Science* 77(11): 2925-2933.
- Verstegen, M. W. A. and W. Van der Hel. 1977. Energy Balances in Groups of Pigs in Relation to Air Velocity and Ambient Temperatures. In *Energy Metabolism in Farm Animals*, 347. ed. M. Vermorel, Clermont-Ferrand: G. de Bussa. The Netherlands: Dordrecht.
- Wheeler, E. F., J. L. Graves, J. T. Zajackowski, J. T. Tyson, D. F. McFarland, and P. Richie. 2001. Protocol for Determination of Environmental Parameters in Animal Housing. In *Livestock Environment VI: Proceeding of the 6th International Symposium*, 359. St. Joseph, MI: ASABE.

APPENDIX A.

Air Velocity Sensor Design

Components for these sensors were purchased individually and assembled and calibrated in the BESS Laboratory (Bioenvironmental Structures and Systems Laboratory) at the University of Illinois. The design constraints included an air velocity measurement range of 0 to 31.3 m/s (0 to 70 mph), output voltage signal of 0 to 10 volts, power requirement of 24 volts, and compatibility with the rest of the system.

Different anemometer components were evaluated before the final equipment was chosen. Common to most automobiles, a Mass Air Flow sensor generally uses a heated wire to measure the velocity in order to determine the volume of incoming air. On an automobile, the air volume measurement is used by the computer to determine engine load, fuel mixture, and other parameters. A simple hot wire works well for this system since the air is always flowing in one direction. Additionally, the platinum hot wire can be superheated to burn off any foreign particles that have accumulated on the wire. The Mass Air Flow sensors are based on the principles of heat transfer across the heated wire. As air velocity increases, the rate of heat transfer increases and more power must be supplied to the wire to maintain the original temperature. Limitations of hot wire anemometers are the directional-dependent characteristics. Omni-directional flows are difficult to measure with a hot wire because different corrections are needed depending on the angle of air velocity to the wire orientation. Additionally, the temperature of the heated wire can skew air velocity measurements and areas of localized heating around the wire can create buoyancy effects and resultant air movement (Funk, 1994). To overcome this drawback of hot wire anemometers, a small glass-bead thermistor can be used in place of a hot wire. A thermistor is more durable than a thin wire and the spherical design can reduce the directional influence.

Thermistors are characterized by the Steinhart-Hart Equation, a 3rd order log polynomial equation using three constants as follows where T_k is the temperature and R is the resistance. A , B and C are constant factors, and called the Steinhart-Hart parameters.

$$\frac{1}{T_K} = A + B \cdot (\ln R) + C \cdot (\ln R)^3 \quad (4)$$

Material type, wire diameter and thermistor shape can affect the thermistor's characteristics. The inverse temperature relationship in this equation indicates that as the temperature rises, the overall resistance decreases.

After reviewing the literature, several circuits were constructed and tested to determine the optimal design. The least complex circuit proved to be the best choice in terms of cost, reliability, and calibration. A small-scale wind tunnel (Model 8390 Bench Top Wind Tunnel, TSI Inc.) was used to test different circuit designs by introducing various air speeds to the sensing mechanisms. As shown in Figure A.1, the circuit consisted of an op-amp, a transistor, and a Wheatstone bridge made up of two resistors and two thermistors.

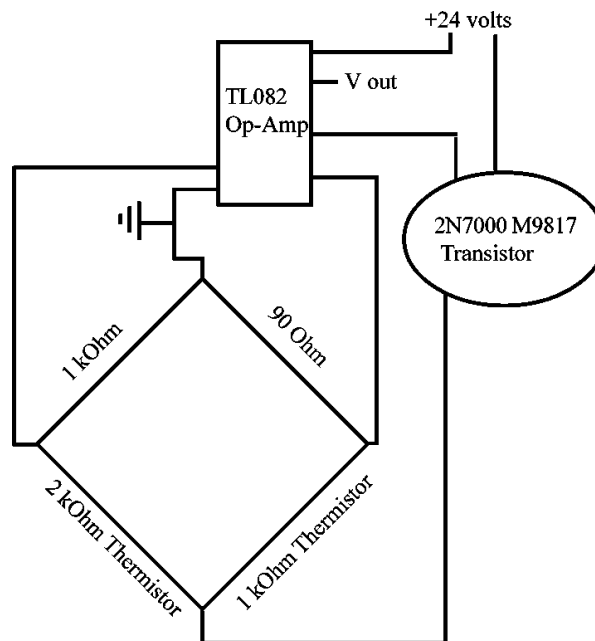


Figure A.1. Air velocity sensor circuit design

The small glass-bead thermistor was heated to 48.88°C by the power coming through the transistor. The faster responding 2 kΩ thermistor was calibrated at 48.88°C and found to have a resistance of 90 Ω. As a result, a 90 Ω fixed resistor was placed on the same side of the bridge as the glass-bead thermistor. A 1 kΩ fixed resistor was placed opposite the 1 kΩ larger-mass, slower-reacting thermistor to balance the bridge. The larger-mass thermistor had similar temperature characteristics but a slower reaction time than the smaller glass bead thermistor. As a result, the ambient temperature effects were equal between both thermistors and helped maintain accurate readings through different ambient temperatures. The fast-responding glass bead thermistor is greatly influenced by changes in air velocity, whereas the larger-mass thermistor is minimally affected. Due to the nature of the Wheatstone bridge, the voltage differences across both sides are identical since they are provided with the same input voltage and are connected to the same ground potential. The difference in voltage measurement occurs across the middle of the bridge. The op-amp conditions and amplifies the output signal from the bridge and allows the voltage differential to be read from the data acquisition system, and the feedback loop provides improved temporal response. Three different spherical glass-bead thermistors were tested from Newark Electronics (30F1722, 23 and 25) with a 1, 2, or 10 kΩ resistance at 25°C, respectively. The thermistor calibration curves and the respective voltage output readings for different air velocities for the three thermistors tested are presented in Figure A.2.

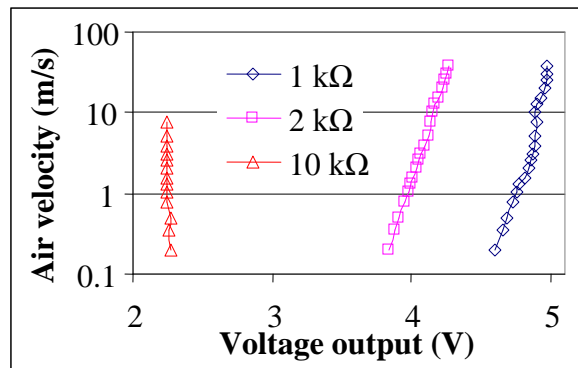


Figure A.2. Thermistor calibration graph

The 1 and 2 k Ω thermistors provided similar output response and these data fit well to an exponential trendline and equation. A best-fit logarithmic line was fitted to each calibration test. The slope of the lines for the 1 k Ω and 2 k Ω thermistors was similar, however, the 2 k Ω thermistor was selected because the equation gave a better fit to the data ($r^2 = 0.99$) compared to the 1 k Ω ($r^2 = 0.94$). Final component selection is presented in Table 1. The project enclosure was used to protect the circuitry from the dusty environment within the trailer. Both thermistors were exposed to the ambient air outside of the project enclosure.

Table A.1. Final air velocity sensor component selection, and part numbers.

Component	Supplier	Part number
90 Ohm resistor	U of I ECE Store	-
1 kOhm resistor	U of I ECE Store	-
1 kOhm NTC thermistor	Newark	10M5326
2 kOhm thermistor	Newark	30F 1723
TL082 Op-Amp	U of I ECE Store	-
2N7000 M9817 transistor	Jameson Electronics	119423
Project enclosure	Radio Shack	270-283a

Air velocity sensor calibration was performed in the BESS Lab. A large-scale fan test chamber was adapted to provide known air velocity in order to calibrate each air velocity sensor. A supply fan provided air into the chamber and screens helped provide uniform air distribution. Different-size nozzles were opened or closed to create air flow rates between 0.033 and 14.157 m³/s. A small duct with a cross-sectional area of 0.12 m² was attached to the chamber and used to provide air velocities between 0.228 and 11.49 m/s; after initial testing, it was determined that higher air velocities would not be expected inside the trailer. Air velocity readings in the column apparatus were compared against a handheld TSI air velocity transducer. Sensor calibration was performed prior to each test in order to maintain accurate measurement and to reduce any drifting in the transducer outputs over time.

Appendix B
Sensor Calibration Procedures

Table B.1. Solar Radiation Calibration Readings.

Handheld Reading		
Lux	Watts/M ²	Output Voltage
271	0.4054	0.0037
320	0.4787	0.00419
490	0.7330	0.00456
647	0.9679	0.00531
699	1.0457	0.00568
1490	2.2290	0.00691
14500	21.692	0.03689
16400	4.5344	0.0422
16500	24.684	0.04269
17100	5.5816	0.04762
18500	27.676	0.07218
20500	30.668	0.05861
25900	38.7464	0.06453
33300	9.8168	0.09192
37400	55.9504	0.12634
50000	74.800	0.18754
71000	106.216	0.3161
76000	113.696	0.29956
81000	121.176	0.32005
104000	155.584	0.47723
109500	163.812	0.48118
110000	164.56	0.49006

1Lux=0.001496 watts/sq. meter

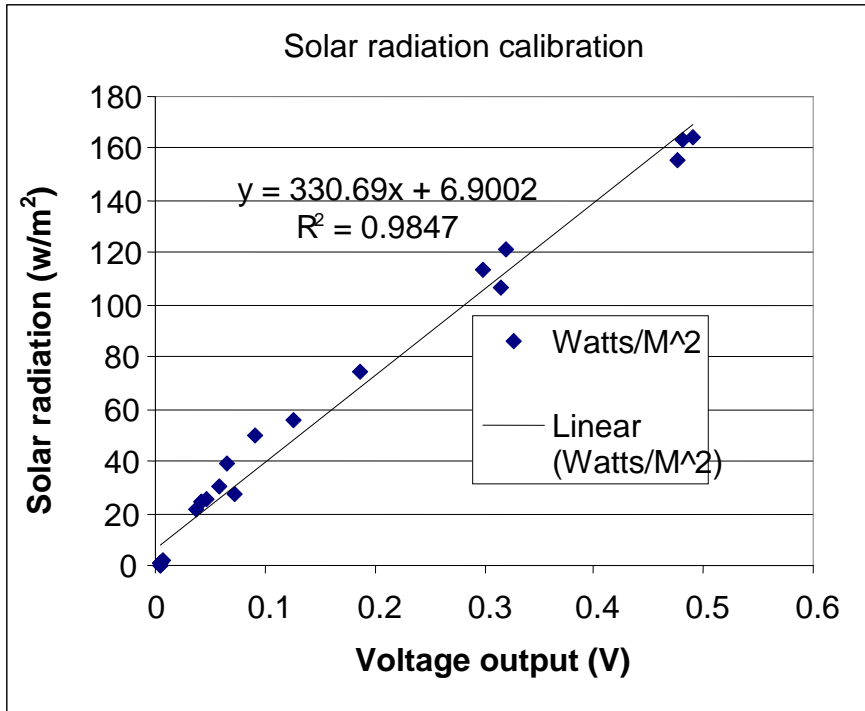


Figure B.1. Solar radiation sensor calibration graph

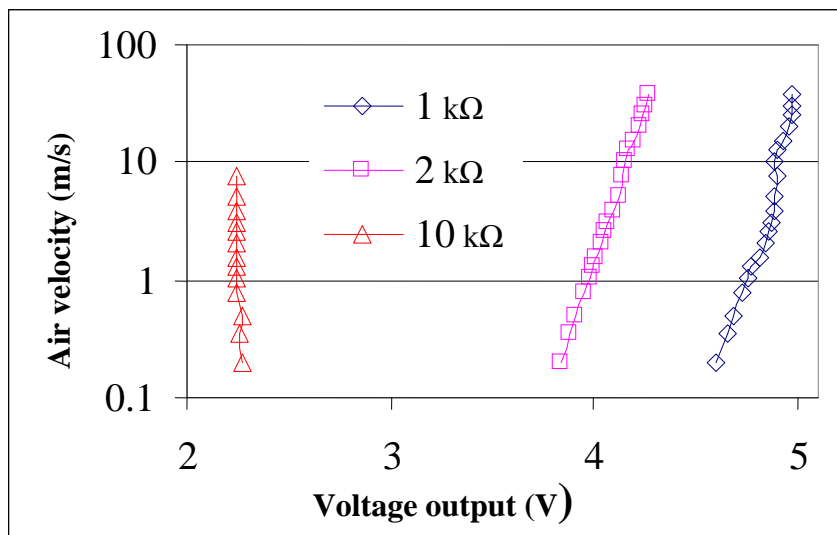


Figure B.2. Air velocity thermistor calibration graph



Figure B.3. Air velocity sensor calibration system

Table B.2. Air velocity thermistor calibration chart.

Plate #	Pressure (mm Hg)	Air velocity			Output voltage		
		(fpm)	(mph)	(m/s)	1kΩ	2KΩ	10KΩ
2	0.199	40	0.45	0.203	4.600	3.84	2.266
2	0.625	70	0.80	0.355	4.649	3.887	2.257
2	1.32	100	1.14	0.508	4.68	3.91	2.273
2	3.04	150	1.70	0.762	4.724	3.946	2.246
2	5.5	200	2.27	1.016	4.755	3.975	2.251
1	0.222	250	2.84	1.270	4.775	3.999	2.243
1	0.321	300	3.41	1.524	4.814	4.015	2.244
1	0.573	400	4.55	2.032	4.841	4.039	2.245
1	0.897	500	5.68	2.540	4.849	4.057	2.244
1	1.3	600	6.82	3.048	4.869	4.072	2.244
1	2.04	750	8.52	3.810	4.884	4.09	2.243
1	3.66	1000	11.36	5.080	4.891	4.129	2.242
1	8.4	1500	17.05	7.620	4.893	4.147	2.245
---	0.271	2000	22.73	10.160	4.88	4.147	
---	0.476	2500	28.41	12.700	4.9	4.172	
---	0.739	3000	34.09	15.240	4.926	4.203	
---	1.06	4000	45.45	20.320	4.955	4.229	
---	2.95	5000	56.82	25.400	4.974	4.234	
---	4.25	6000	68.18	30.480	4.974	4.255	
---	6.64	7500	85.23	38.100	4.974	4.271	
		Thermistor	Equation				R ²
		1kΩ	y=8e ^{-29x}				0.939
		2kΩ	y= 1E-21e ^{12.111x}				0.9957
		10kΩ	y=3E+81 ^{-81.226x}				0.5886

Table B.3. Fan chamber calibration air velocity values.

# Open Nozzles	Nozzle diameter, cm (in)	Pressure drop Pa (in. H ₂ O)	Airflow m ³ /s (cfm)	Velocity (mph, m/s)
1	5.08 (2)	0 (0.0)	0 (0)	0.00 (0.00)
1	5.08 (2)	124.4 (0.5)	0.03 (60)	0.51 (0.23)
1	5.08 (2)	373.2 (1.5)	0.05 (105)	0.90 (0.40)
1	5.08 (2)	622.0 (2.5)	0.06 (136)	1.16 (0.52)
1	5.08 (2)	995.2 (4.0)	0.08 (172)	1.47 (0.66)
1	10.16 (4)	124.4 (0.5)	0.11 (244)	2.08 (0.93)
1	10.16 (4)	248.8 (1.0)	0.16 (345)	2.94 (1.32)
1	10.16 (4)	497.6 (2.0)	0.23 (489)	4.17 (1.86)
1	10.16 (4)	746.4 (3.0)	0.28 (599)	5.11 (2.28)
1	10.16 (4)	995.2 (4.0)	0.33 (692)	5.90 (2.64)
1	10.16 (4)	1244.0 (5.0)	0.36 (773)	6.59 (2.95)
1	10.16 (4)	1492.8 (6.0)	0.40 (846)	7.22 (3.23)
1	20.32 (8)	124.4 (0.5)	0.46 (981)	8.37 (0.74)
1	20.32 (8)	248.8 (1.0)	0.66 (1390)	11.86 (5.30)
1	20.32 (8)	497.6 (2.0)	0.93 (1967)	16.78 (7.50)
1	20.32 (8)	746.4 (3.0)	1.14 (2408)	20.54 (9.18)
1	20.32 (8)	995.2 (4.0)	1.31 (2778)	23.70 (10.59)
1	20.32 (8)	1244.0 (5.0)	1.46 (3103)	26.47 (11.83)

Table B.4. July air velocity sensor calibration values.

Air Velocity mph m/s		Sensor/Compartment number											
		1		2		3		4		5		6	
		Deck Location	Top Front	Top Middle	Top Middle	Top Middle	Top Rear	Bottom Front	Bottom Middle	Bottom Middle	Bottom Middle	Bottom Rear	Bottom Rear
5	2.24	4.16	7.98	6.57	7.99	8.01	7.40	7.05	7.40	8.43	7.36	8.02	
10	4.48	4.23	8.48	6.93	8.60	8.65	7.89	7.55	7.89	8.84	7.83	8.63	
15	6.72	4.29	8.79	7.26	9.05	9.01	8.19	7.81	8.19	8.89	8.22	9.05	
20	8.96	4.30	8.97	7.24	9.25	9.28	8.43	7.96	8.43	9.17	8.41	0.17	
30	13.44	4.37	9.36	7.77	9.57	9.80	8.74	8.39	8.74	9.52	8.84	0.68	
40	17.92	4.41	9.51	7.99	9.94	10.12	8.98	8.57	8.98	9.75	9.11	10.01	
50	22.40	4.43	9.77	8.14	10.24	10.30	9.11	8.79	9.11	9.99	9.17	10.34	
60	26.88	4.45	9.93	8.26	10.43	10.49	9.21	8.86	9.21	10.14	9.41	10.50	
70	31.36	4.46	10.01	8.39	10.60	10.67	9.26	8.90	9.26	10.25	9.52	10.51	

$$\text{Air Velocity (m/s)} = A * e^{(B * \text{voltage})}$$

Compartment	1	2	3	4	5	6	7	8	9	10	11
Deck Location	Top Front	Top Middle	Top Middle	Top Middle	Top Rear	Bottom Front	Bottom Middle	Bottom Middle	Bottom Middle	Bottom Rear	Bottom Rear
A	4.00E-15	2.00E-04	6.00E-04	1.70E-03	2.20E-03	2.00E-04	4.00E-04	2.00E-04	7.00E-05	8.00E-04	1.80E-03
B	8.3535	1.2742	1.3900	1.0080	0.9753	1.3669	1.3585	1.3669	1.3586	1.1903	0.9993

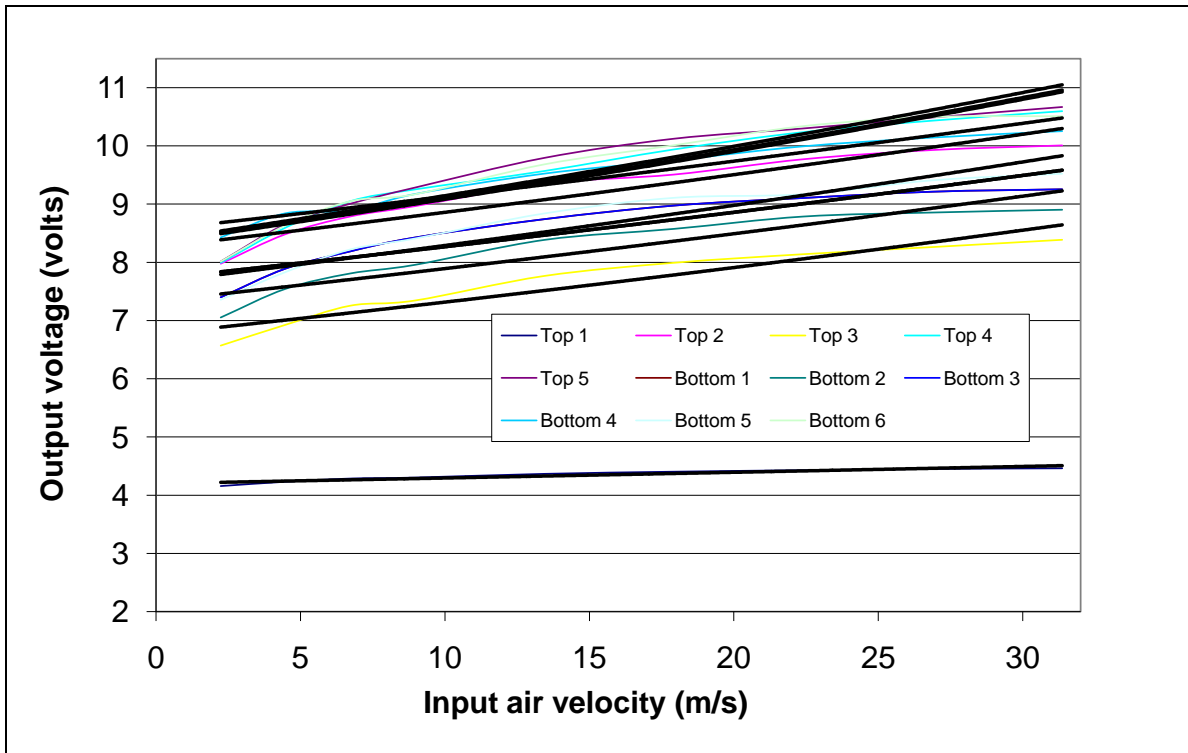


Figure B.4. July air velocity sensor calibration graph

Table B.5. November air velocity sensor calibration values.

		Sensor/Compartment number										
		1	2	3	4	5	1	2	3	4	5	6
Deck	Location	Top Front	Top Middle	Top Middle	Top Middle	Top Rear	Bottom Front	Bottom Middle	Bottom Middle	Bottom Middle	Bottom Rear	Bottom Rear
Air velocity												
mph	m/s											
0.51	0.23	3.99	6.65	6.85	6.72	6.80	6.73	6.67	6.29	6.51	6.45	6.79
0.90	0.40	4.04	6.77	7.17	7.02	7.13	6.98	6.95	6.57	6.81	6.75	7.02
1.16	0.52	4.05	6.97	7.30	7.17	7.27	7.19	7.15	6.71	6.96	6.89	7.18
1.47	0.66	4.08	7.12	7.45	7.34	7.40	7.31	7.30	6.84	7.09	7.01	7.33
2.08	0.93	4.11	7.26	7.62	7.46	7.60	7.48	7.45	6.98	7.22	7.15	7.49
2.94	1.32	4.15	7.44	7.82	7.67	7.81	7.74	7.65	7.20	7.44	7.37	7.70
4.17	1.87	4.19	7.70	8.05	7.89	8.06	8.01	7.90	7.41	7.70	7.55	7.88
5.11	2.29	4.21	7.82	8.19	8.14	8.18	8.14	8.07	7.53	7.86	7.68	7.99
5.90	2.64	4.22	7.94	8.33	8.16	8.30	8.23	8.16	7.61	7.97	7.80	8.12
6.59	2.95	4.23	8.07	8.44	8.22	8.34	8.34	8.23	7.66	8.03	7.86	8.23
7.22	3.23	4.23	8.11	8.49	8.28	8.41	8.33	8.28	7.70	8.09	7.92	8.24
8.37	3.75	4.25	8.24	8.60	8.48	8.58	8.41	8.39	7.92	8.22	8.03	8.35
11.86	5.31	4.28	8.45	8.88	8.71	8.81	8.70	8.70	8.15	8.47	8.20	8.57
16.78	7.52	4.32	8.74	9.20	9.00	9.19	9.07	8.98	8.38	8.76	8.55	8.88
20.54	9.20	4.35	8.88	9.40	9.16	9.40	9.24	9.17	8.51	8.94	8.71	9.01
23.70	10.62	4.36	8.94	9.54	9.21	9.50	9.36	9.29	8.61	9.08	8.81	9.09
26.47	11.86	4.36	8.95	9.60	9.31	9.51	9.43	9.33	8.63	9.09	8.85	9.11

Air velocity (m/s) = A*exp(B*voltage)

Compartment	1	2	3	4	5	1	2	3	4	5	6
Deck	Top	Top	Top	Top	Top	Bottom	Bottom	Bottom	Bottom	Bottom	Bottom
Location	Front	Middle	Middle	Middle	Rear	Front	Middle	Middle	Middle	Rear	Rear
A	7.00E-19	2.00E-05	5.00E-05	3.00E-05	5.00E-05	5.00E-05	4.00E-05	2.00E-05	5.00E-05	2.00E-05	1.00E-05
B	10.3370	1.5541	1.3930	1.4788	1.3983	1.4165	1.4396	1.6150	1.4684	1.6080	1.6198

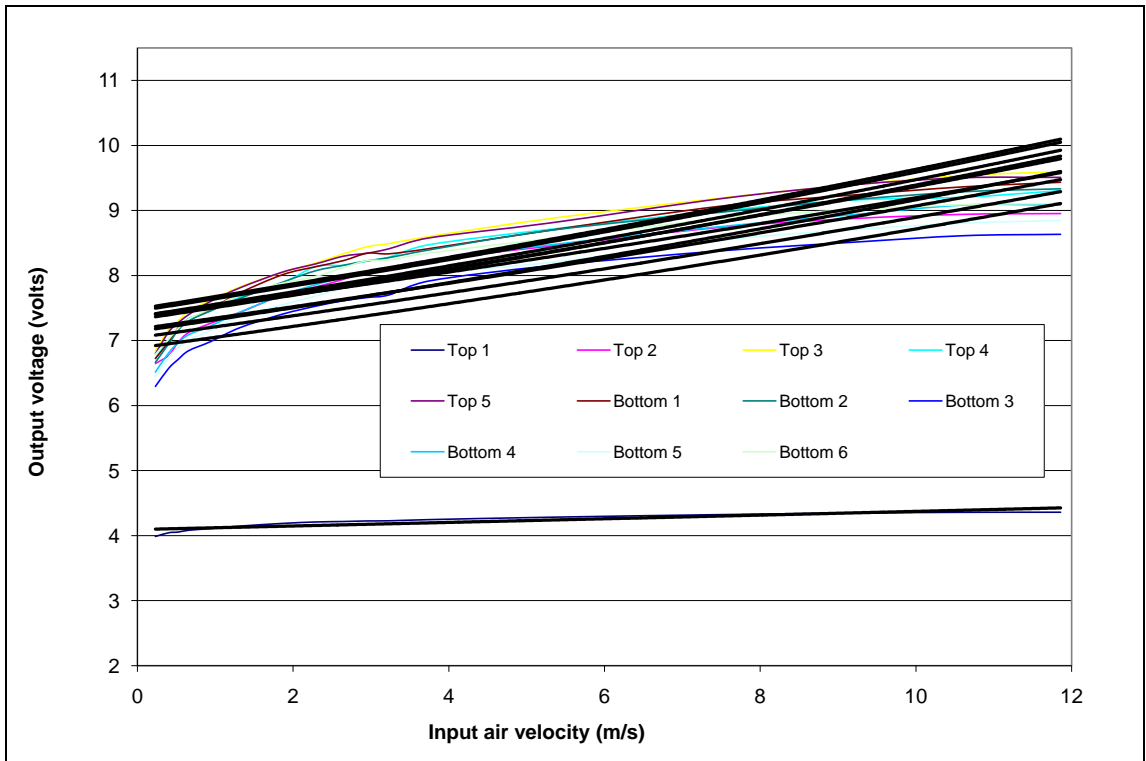


Figure B.5 November air velocity sensor calibration graph

Table B.6. Long wire color codes for boxes 1-12

Box 1			Box 5		
Pin #	Wire color	Description	Pin #	Wire color	Description
1	Red	+ 24 VDC	1	Red	+ 24 VDC
2	Black	Input Ground	2	Black	Input Ground
3			3		
4	Blue	Temperature	4	Blue	Temperature
5	Orange	R.H.	5	Orange	R.H.
6	Black	Ground	6	Black	Ground
7			7		
8	White	CO2	8	White	CO2
9	Black	Ground	9	Black	Ground
10			10		
11	Green	Ground IR sensors	11		
12			12		
13	Yellow	Air Velocity	13	Yellow	Air Velocity
14	Black	Ground	14	Black	Ground
15	Orange	IR Temp-Roof	15		
16	Blue	IR Temp-Front	16		
17	Green	IR Temp-Pig	17	Green	IR Temp-Pig
18	Ground		18	Black	Ground
19	Yellow	IR Temp-Side			

Boxes 2 - 11			Box 12		
Pin #	Wire color	Description	Pin #	Wire color	Description
1	Red	+ 24 VDC	1	Red	+ 24 VDC
2	Black	Input Ground	2	Black	Input Ground
3			3		
4	Blue	Temperature	4	Blue	Temperature
5	Brown	R.H.	5	Orange	R.H.
6	Black	Ground	6	Black	Ground
7			7		
8	White	CO2	8	White	CO2
9	Green	Ground	9	Black	Ground
10			10		
11			11		
12			12		
13	Yellow	Air Velocity	13	Yellow	+ Solar
14	Black	Ground	14	Black	- Solar
			15		
			16		
			17	Green	Pulse GPS Input

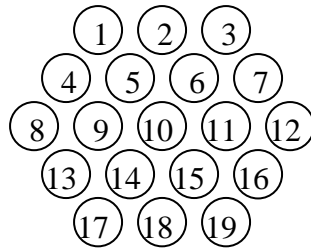


Figure B.6. Pin location numbering on female pins

Table B.7. Individual box color codes.

Pin #	Color	Description
Temperature and Relative Humidity Sensors		
4	Brown	0 to 10 VDC output Relative Humidity
5	Blue	0 to 10 VDC output Temperature
6	Green	Ground
2	Black	Ground
1	Red	+ 24 VDC Input
Carbon Dioxide Sensors		
8	White	0 to 10 VDC output Carbon Dioxide
9	Green	Ground
2	Black	Ground
1	Red	+ 24 VDC Input
Air Velocity Sensors		
13	White	0 to 10 V output Air Velocity
14	Green	Ground
2	Black	Ground
1	Red	+ 24 VDC Input
Infrared Temperature Sensors		
17	White	0 to 5 VDC output Temperature
18	Black	Ground
2	Green	Ground
1	Red	+ 24 VDC Input
Solar Radiation Sensor		
13	Blue	+ Solar
14	Green	- Solar
GPS-Truck Speed		
17	Orange	GPS Pulse output
2	Black	Ground
1	Red	+ 24 VDC Input

Table B.8. Main box channel numbers, labels, range, units and wire colors.

Physical channel	User label	Range	Units	Wire color
PD1_A01L	TEMP_1	-10.0 to 10.0	Volts	Blue
PD1_A01H	RH_1	-10.0 to 10.0	Volts	Orange
PD1_A02L	CO2_1	-10.0 to 10.0	Volts	White
PD1_A02H	WIND_1	-10.0 to 10.0	Volts	Yellow
PD1_A03L	IRTEMP_1P	-10.0 to 10.0	Volts	Red
PD1_A03H	IRTEMP_1Roof	-10.0 to 10.0	Volts	Red
PD1_A04L	IRTEMP_2Front	-10.0 to 10.0	Volts	Red
PD1_A04H	IRTEMP_3Side	-10.0 to 10.0	Volts	Red
PD1_A05L	TEMP_2	-10.0 to 10.0	Volts	Blue
PD1_A05H	RH_2	-10.0 to 10.0	Volts	Orange
PD1_A06L	CO2_2	-10.0 to 10.0	Volts	White
PD1_A06H	WIND_2	-10.0 to 10.0	Volts	Yellow
PD1_A07L	TEMP_3	-10.0 to 10.0	Volts	Blue
PD1_A07H	RH_3	-10.0 to 10.0	Volts	Orange
PD1_A08L	CO2_3	-10.0 to 10.0	Volts	White
PD1_A08H	WIND_3	-10.0 to 10.0	Volts	Yellow
PD1_A09L	TEMP_4	-10.0 to 10.0	Volts	Blue
PD1_A09H	RH_4	-10.0 to 10.0	Volts	Orange
PD1_A10L	CO2_4	-10.0 to 10.0	Volts	White
PD1_A10H	WIND_4	-10.0 to 10.0	Volts	Yellow
PD1_A11L	TEMP_6	-10.0 to 10.0	Volts	Blue
PD1_A11H	RH_6	-10.0 to 10.0	Volts	Orange
PD1_A12L	CO2_6	-10.0 to 10.0	Volts	White
PD1_A12H	WIND_6	-10.0 to 10.0	Volts	Yellow
PD1_A13L	TEMP_7	-10.0 to 10.0	Volts	Blue
PD1_A13H	RH_7	-10.0 to 10.0	Volts	Orange
PD1_A14L	CO2_7	-10.0 to 10.0	Volts	White
PD1_A14H	WIND_7	-10.0 to 10.0	Volts	Yellow
PD1_A15L	TEMP_8	-10.0 to 10.0	Volts	Blue
PD1_A15H	RH_8	-10.0 to 10.0	Volts	Orange
PD1_A16L	CO2_8	-10.0 to 10.0	Volts	White
PD1_A16H	WIND_8	-10.0 to 10.0	Volts	Yellow
PD1_A17L	TEMP_9	-10.0 to 10.0	Volts	Blue
PD1_A17H	RH_9	-10.0 to 10.0	Volts	Orange
PD1_A18L	CO2_9	-10.0 to 10.0	Volts	White
PD1_A18H	WIND_9	-10.0 to 10.0	Volts	Yellow
PD1_A19L	TEMP_10	-10.0 to 10.0	Volts	Blue
PD1_A19H	RH_10	-10.0 to 10.0	Volts	Orange
PD1_A20L	CO2_10	-10.0 to 10.0	Volts	White
PD1_A20H	WIND_10	-10.0 to 10.0	Volts	Yellow
PD1_A21L	TEMP_5	-10.0 to 10.0	Volts	Blue
PD1_A21H	RH_5	-10.0 to 10.0	Volts	Orange
PD1_A22L	CO2_5	-10.0 to 10.0	Volts	White
PD1_A22H	WIND_5	-10.0 to 10.0	Volts	Yellow
PD1_A23L	IR_5	-10.0 to 10.0	Volts	Red
PD1_A23H	Nothing1			
PD1_A24L	TEMP_11	-10.0 to 10.0	Volts	Blue

PD1_A24H	RH_11	-10.0 to 10.0	Volts	Orange
PD1_A25L	CO2_11	-10.0 to 10.0	Volts	White
PD1_A25H	WIND_11	-10.0 to 10.0	Volts	Yellow
PD1_A26L	TEMP_OUT	-10.0 to 10.0	Volts	Blue
PD1_A26H	RH_OUT	-10.0 to 10.0	Volts	Orange
PD1_A27L	CO2_OUT	-10.0 to 10.0	Volts	White
PD1_A27H	Nothing			
PD1_A28	SOLAR	101.2 to -101.2	Volts	Blue/Green
PD1_A29	Out_thermo	Type T	Deg C	Blue
PD1_A30	thermo_out	Type T	Deg C	Blue
PD1_F4	GPS	0 to ∞	Frequency	Yellow

Table B.9. Sensor offset and scale measurements for data conversion.

Temperature (Sensors 1-6 and 8-12)	0 VDC= -40 deg C 10 VDC= 60 deg C Offset = -40.0 Scale = 10
Temperature (Sensor 7)	0 VDC= -20 deg C 10 VDC= 80 deg C Offset = -20.0 Scale = 10
Relative humidity	0 VDC= 0% Relative Humidity 10 VDC= 100% Relative Humidity Offset = 0 Scale = 10
Carbon dioxide	0 VDC= 0 ppm 10 VDC= 5000 ppm Offset = 0 Scale = 500
Air velocity	Individual Calibrations See Calibration Index
Infrared temperature	0 VDC= -10 deg C 5 VDC= 90 deg C Offset = -10.0 Scale = 20
Solar radiation (July and August)	Multiplication= -10.12 Resistance = 604 Ω See Calibration Index
Solar radiation (October-April)	Multiplication= -10.12 Resistance = 129 Ω 16.76 Watts/M ² /mV
GPS	1 pulse per meter recorded pulses per second

APPENDIX C

Schematics of Model Outputs

Figure C.1. Airflow patterns through the longitudinal section in the center of the trailer during transport.

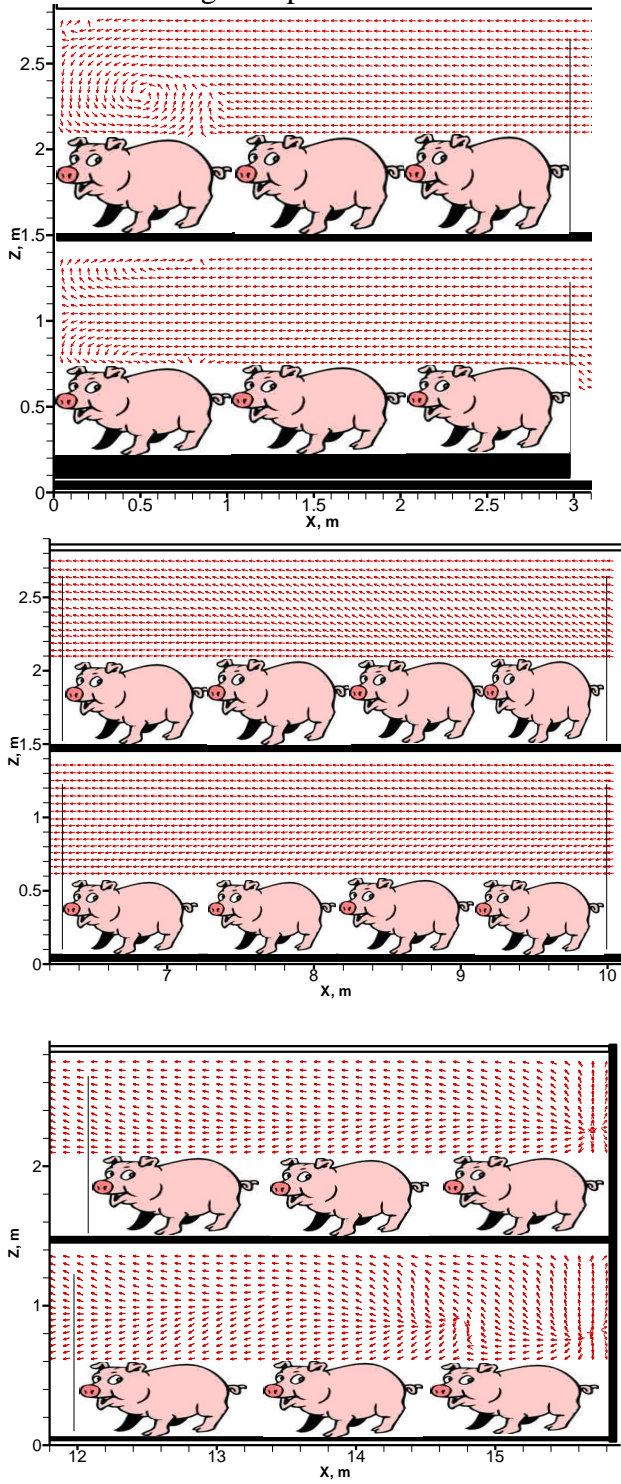


Figure C.2. Airflow patterns through the transverse sections of the trailer during transport.

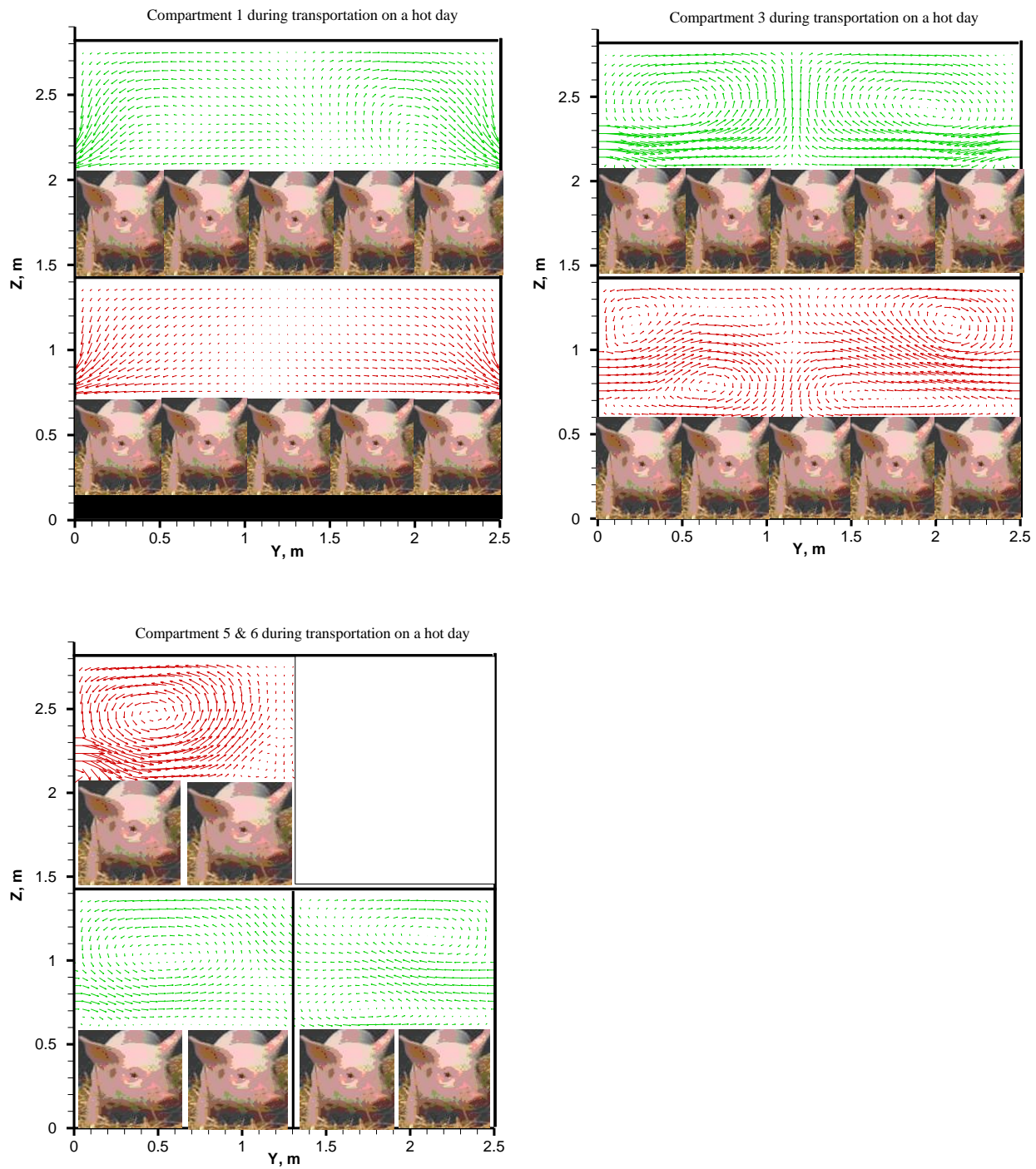


Figure C.3. Air velocity through the longitudinal section in the center of the trailer during transport on a) hot, b) mild, and c) cold days [Simulations 1, 6, and 11, respectively].

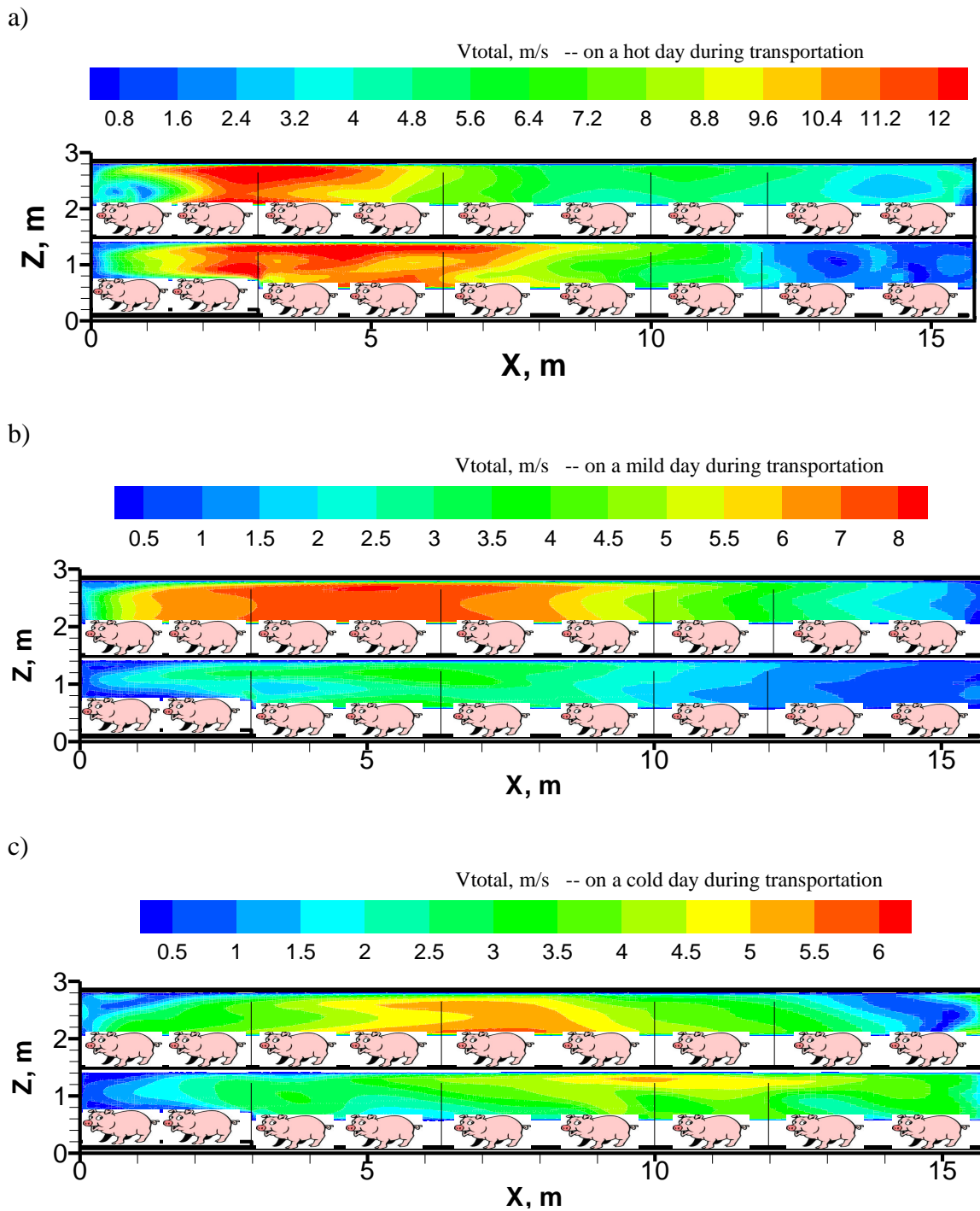
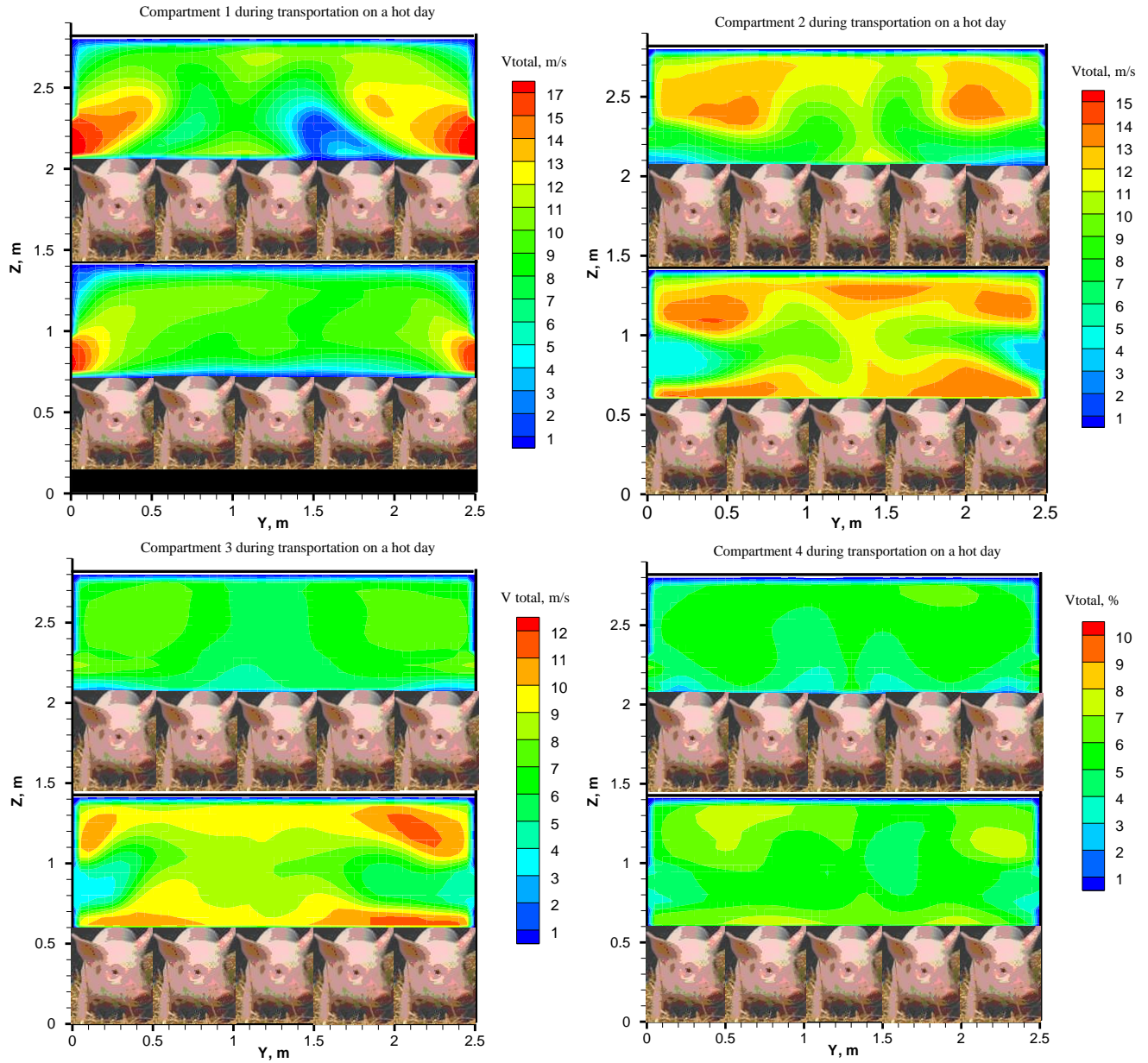


Figure C.4. Air velocity through the transverse sections of the trailer during transport on a hot day [Simulation 1].



Compartment 5 & 6 during transportation on a hot day

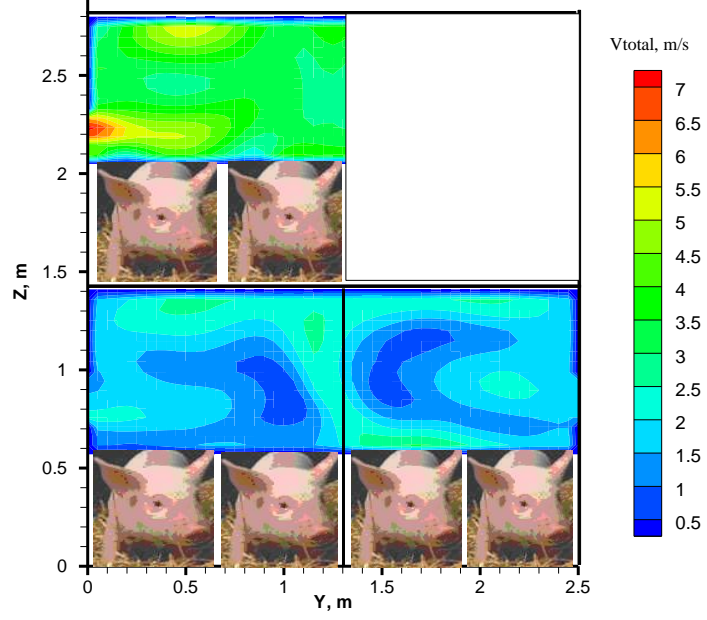
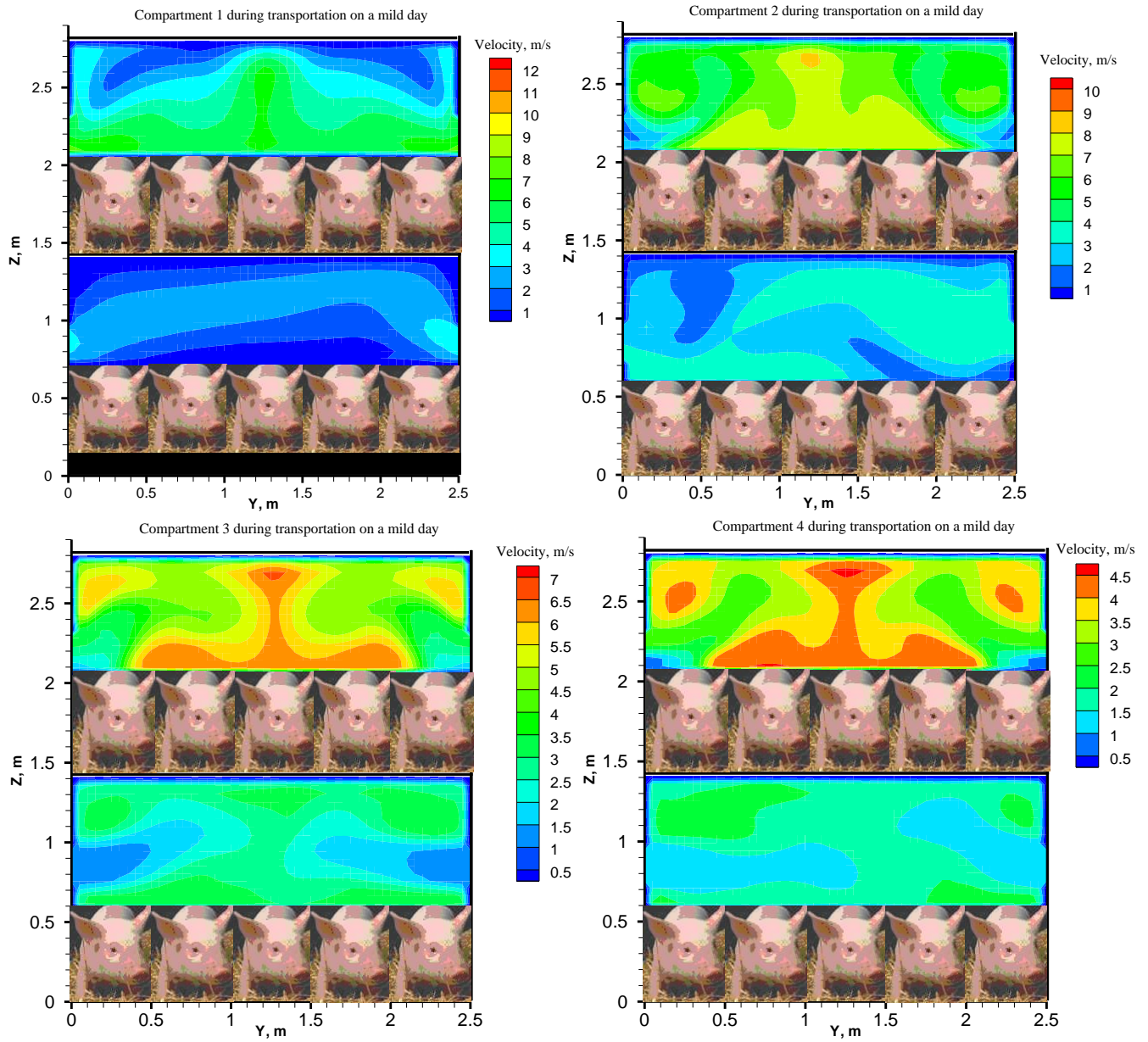


Figure C.5. Air velocity through the transverse sections of the trailer during transport on a mild day [Simulation 6].



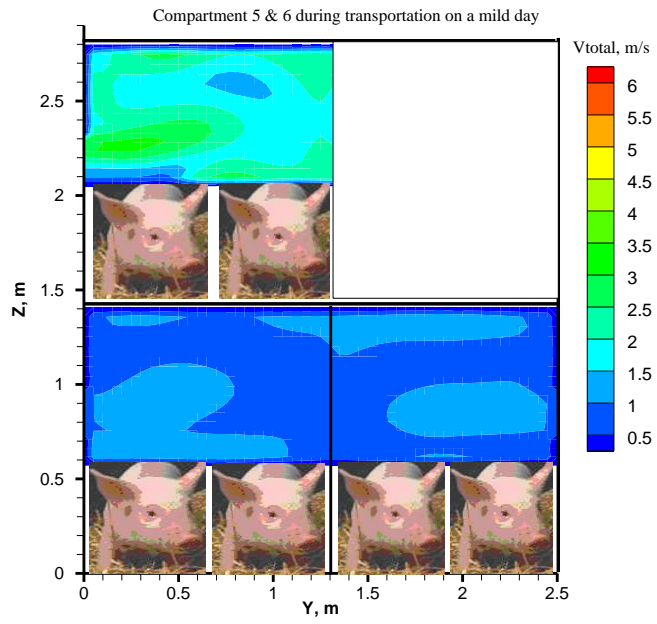
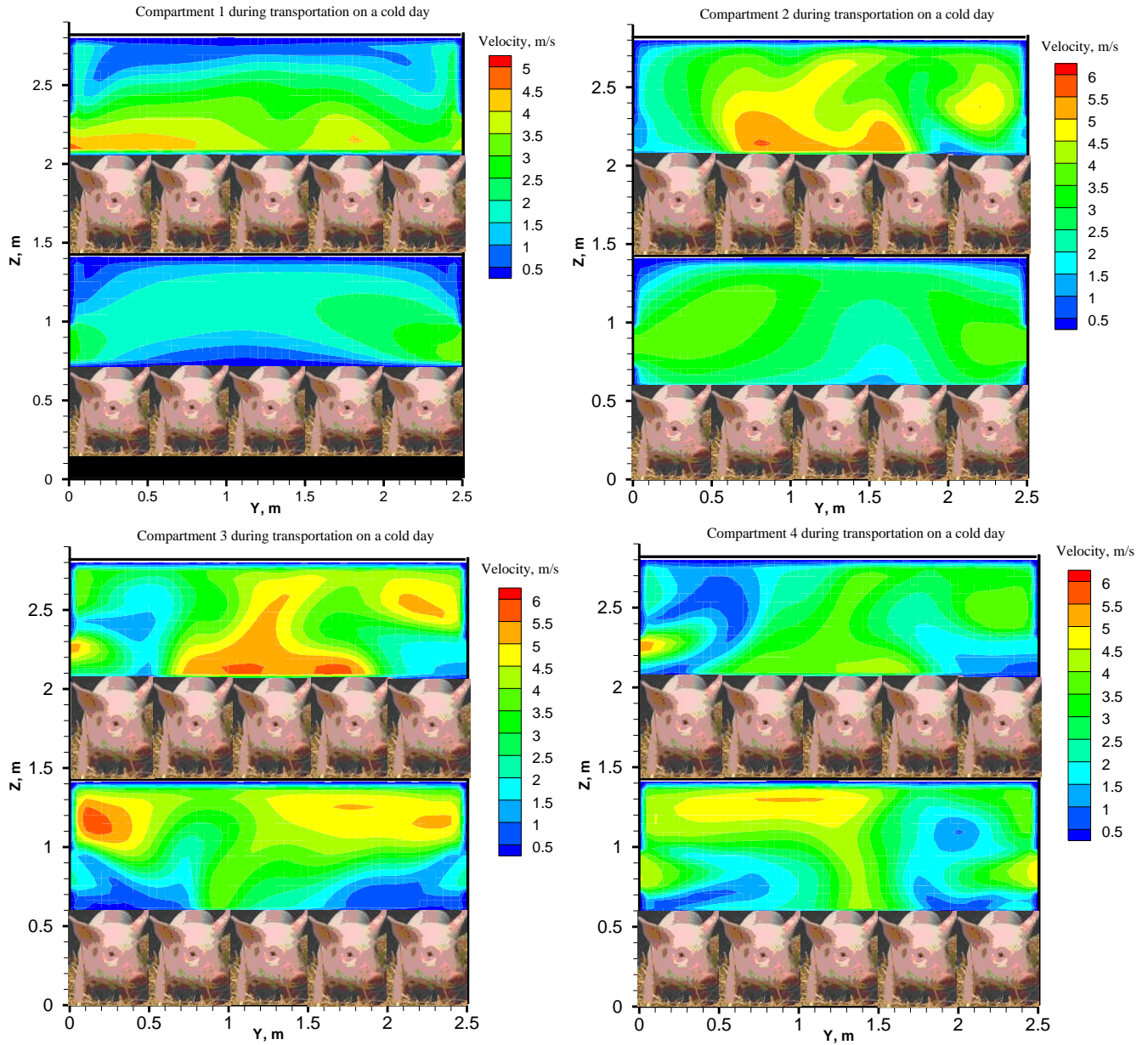


Figure C.6. Air velocity through the transverse sections of the trailer during transport on a cold day [Simulation 11].



Compartment 5 & 6 during transportation on a cold day

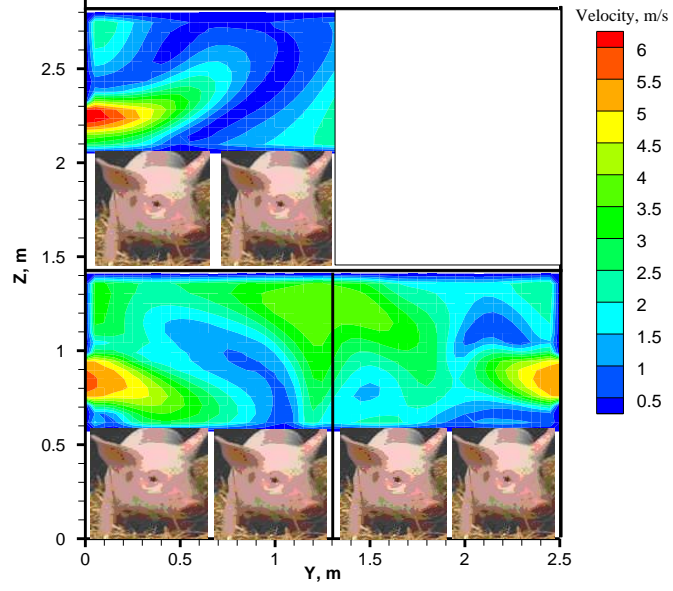


Figure C.7. Air temperature through the longitudinal section in the center of the trailer during transport on a) hot, b) mild, and c) cold days [Simulations 1, 6, and 11, respectively].

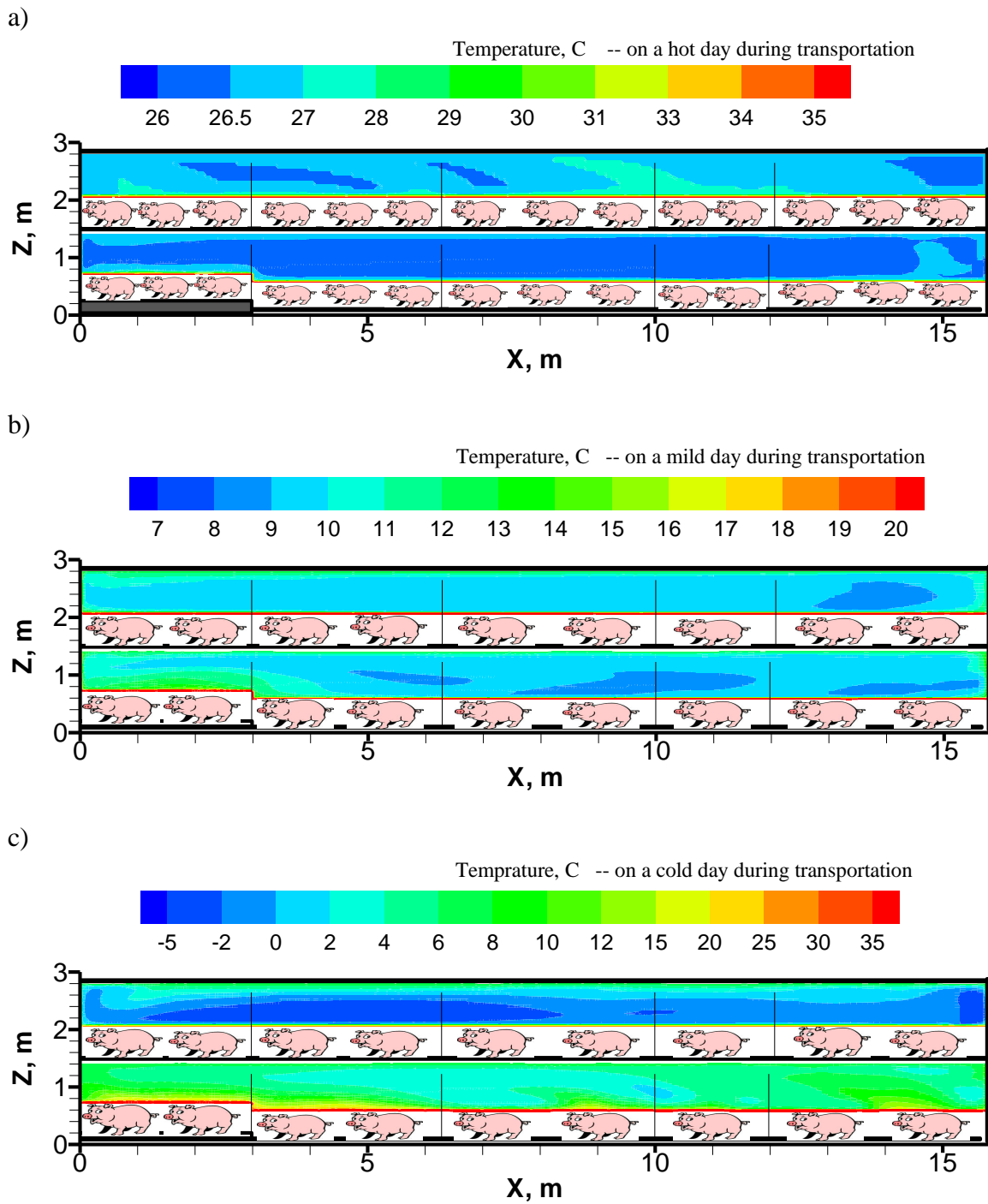


Figure C.8. Air temperature through the transverse sections of the trailer during transport on a hot day [Simulation 1].

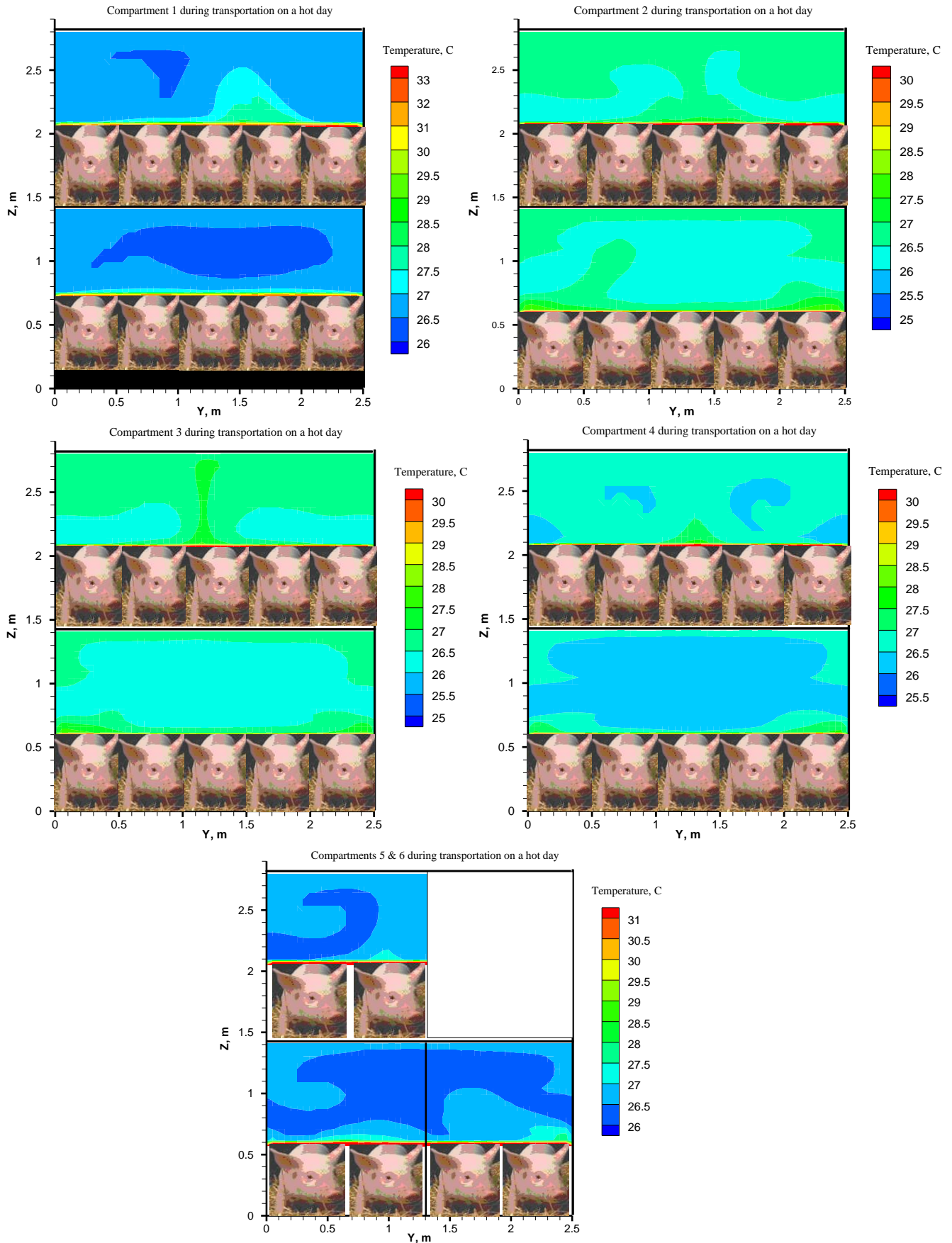
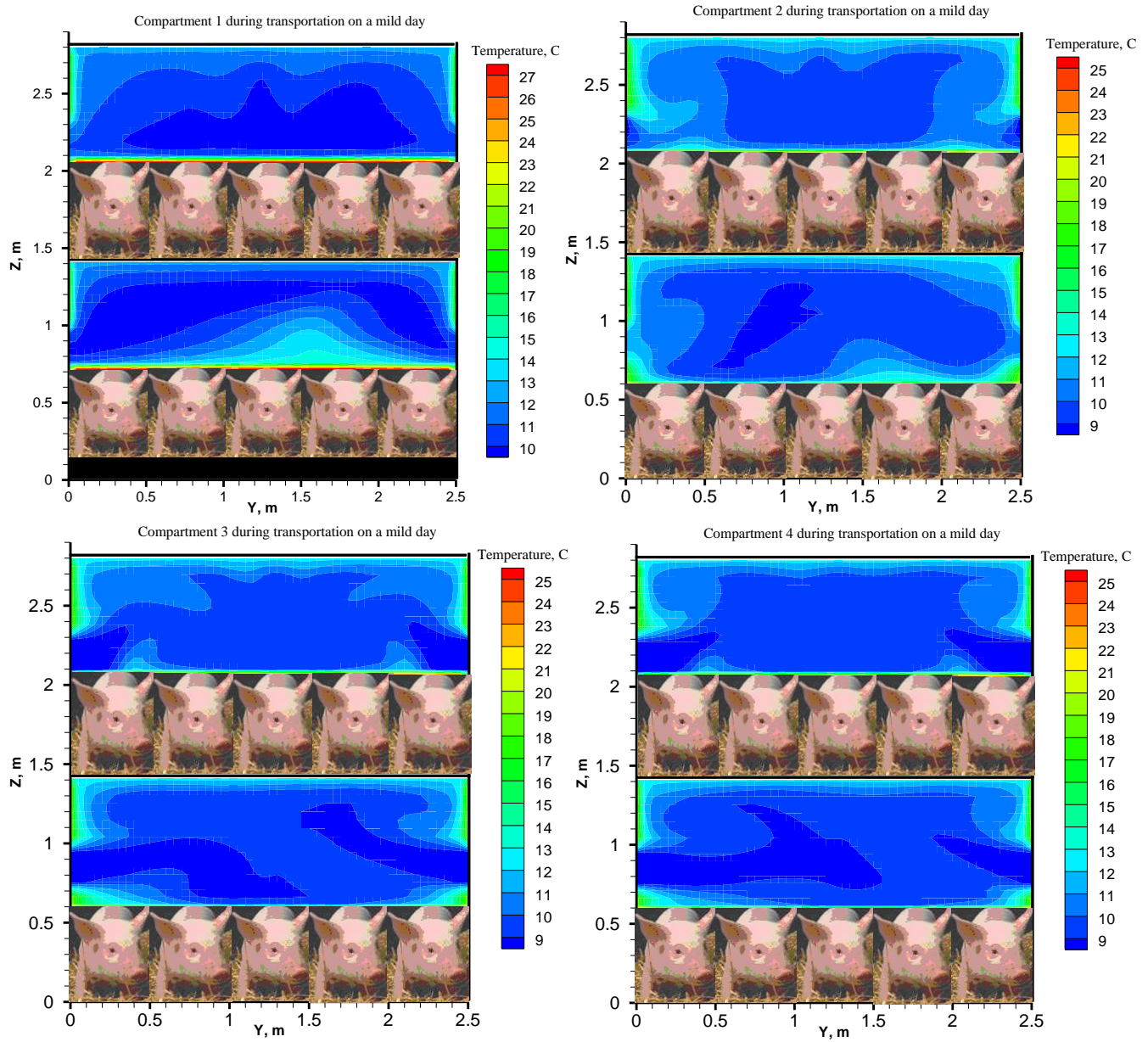


Figure C.9. Air temperature through the transverse sections of the trailer during transport on a mild day [Simulation 6].



Compartment 5 & 6 during transportation on a mild day

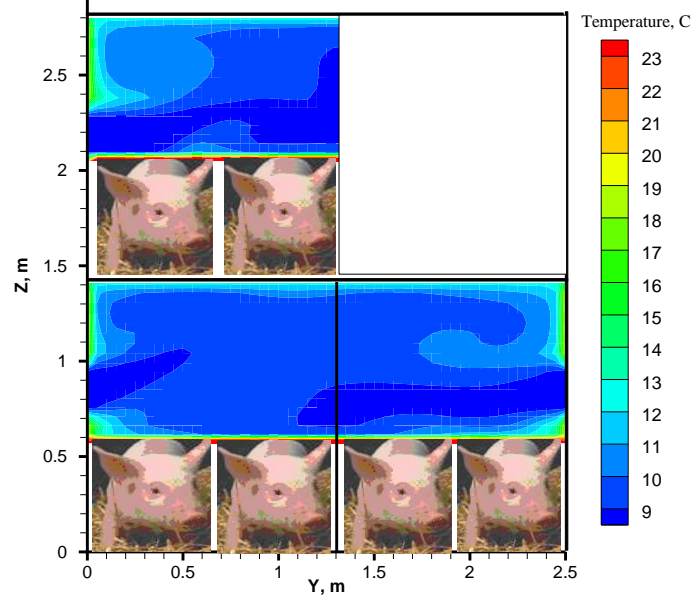


Figure C.10. Air temperature through the transverse sections of the trailer during transport on a cold day [Simulation 11].

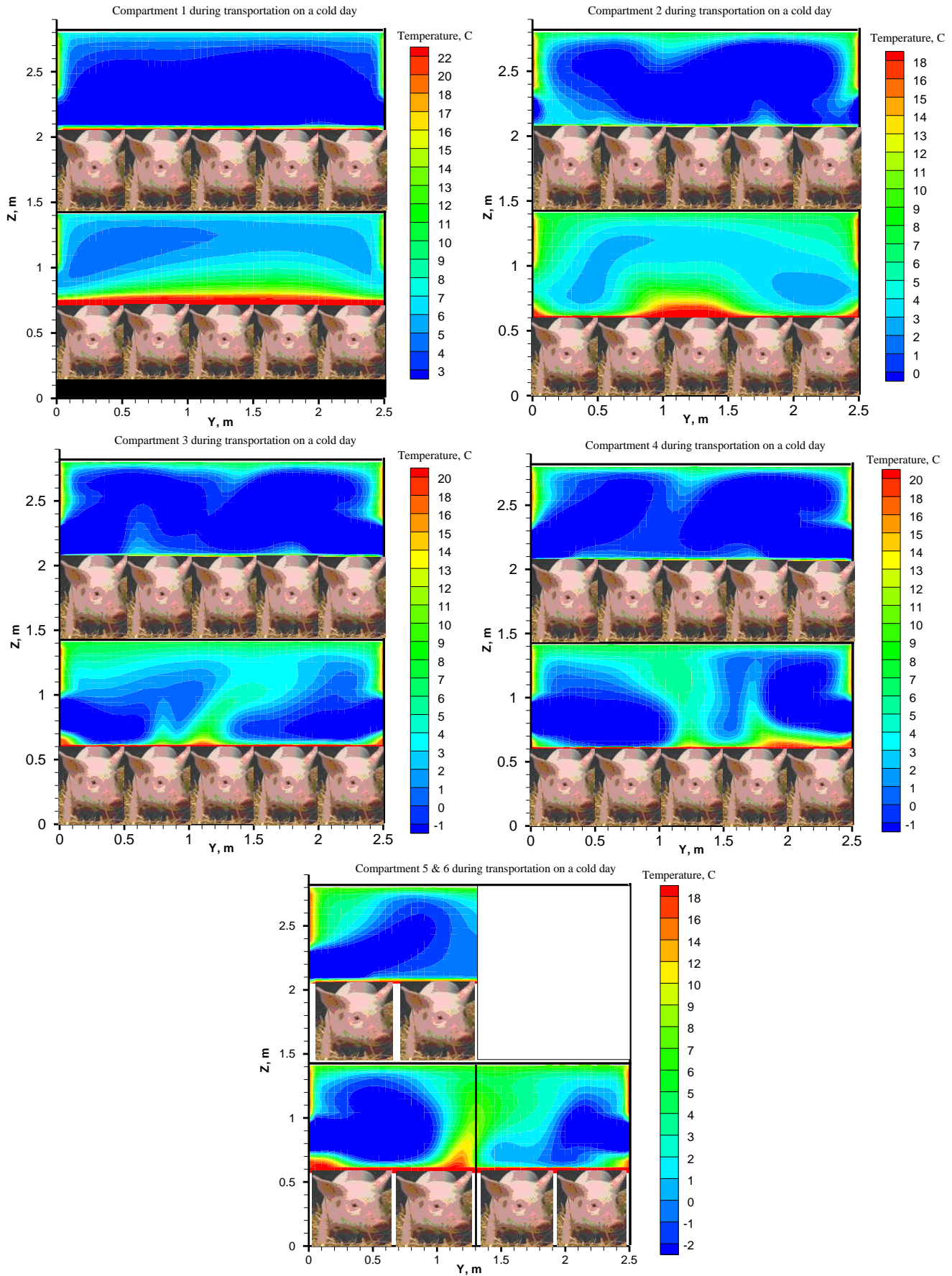
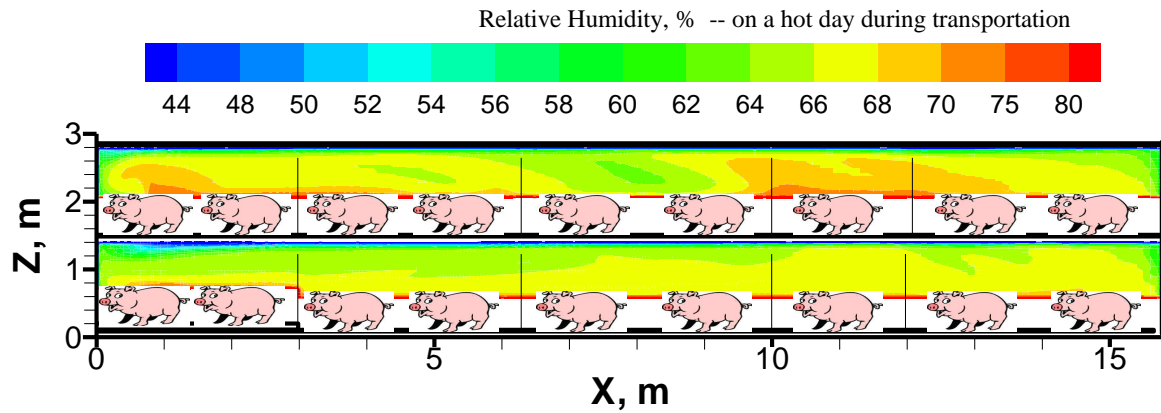
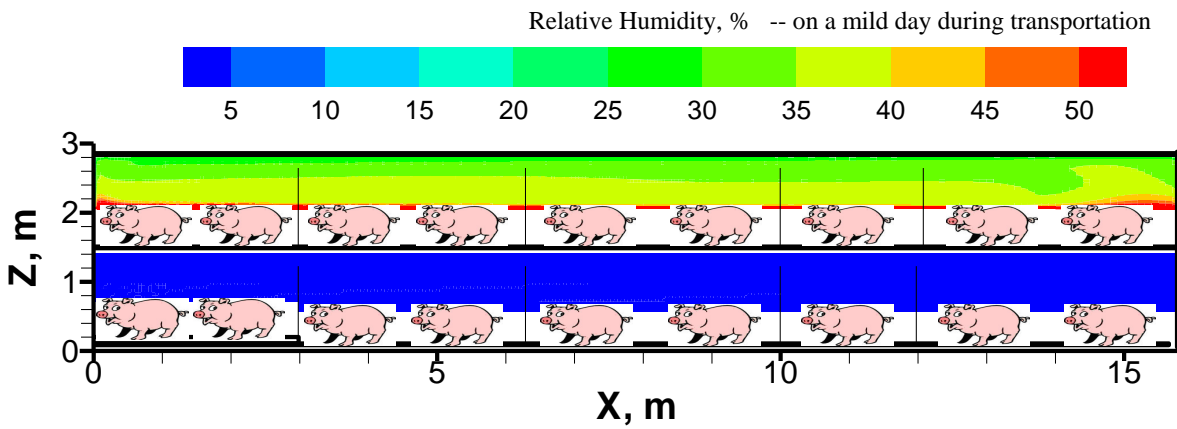


Figure C.11. Air relative humidity through the longitudinal section in the center of the trailer during transport on a) hot, b) mild, and c) cold days [Simulations 1, 6, and 11, respectively].

a)



b)



c)

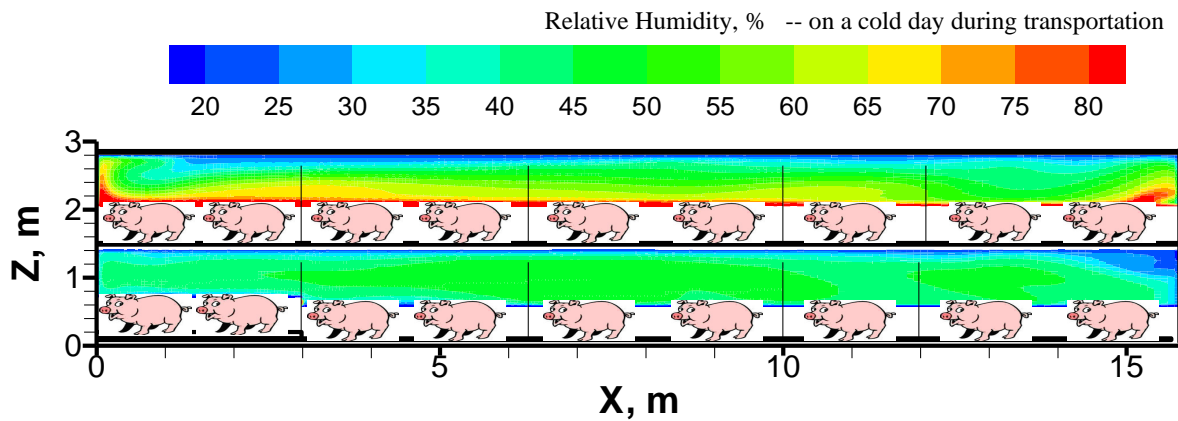


Figure C.12. Air relative humidity through the transverse sections of the trailer during transport on a hot day [Simulation 1].

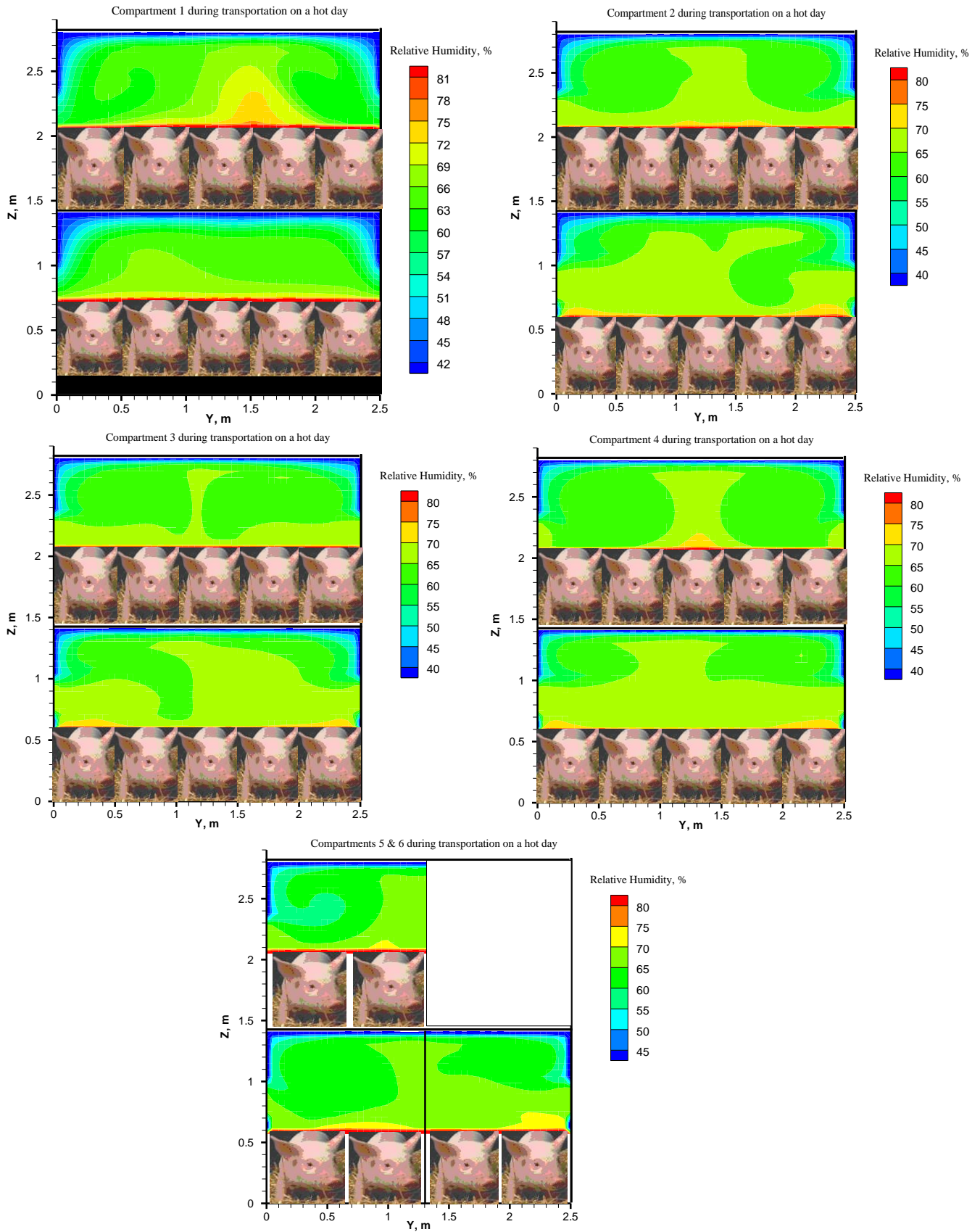


Figure C.13. Air relative humidity through the transverse sections of the trailer during transport on a mild day [Simulation 6].

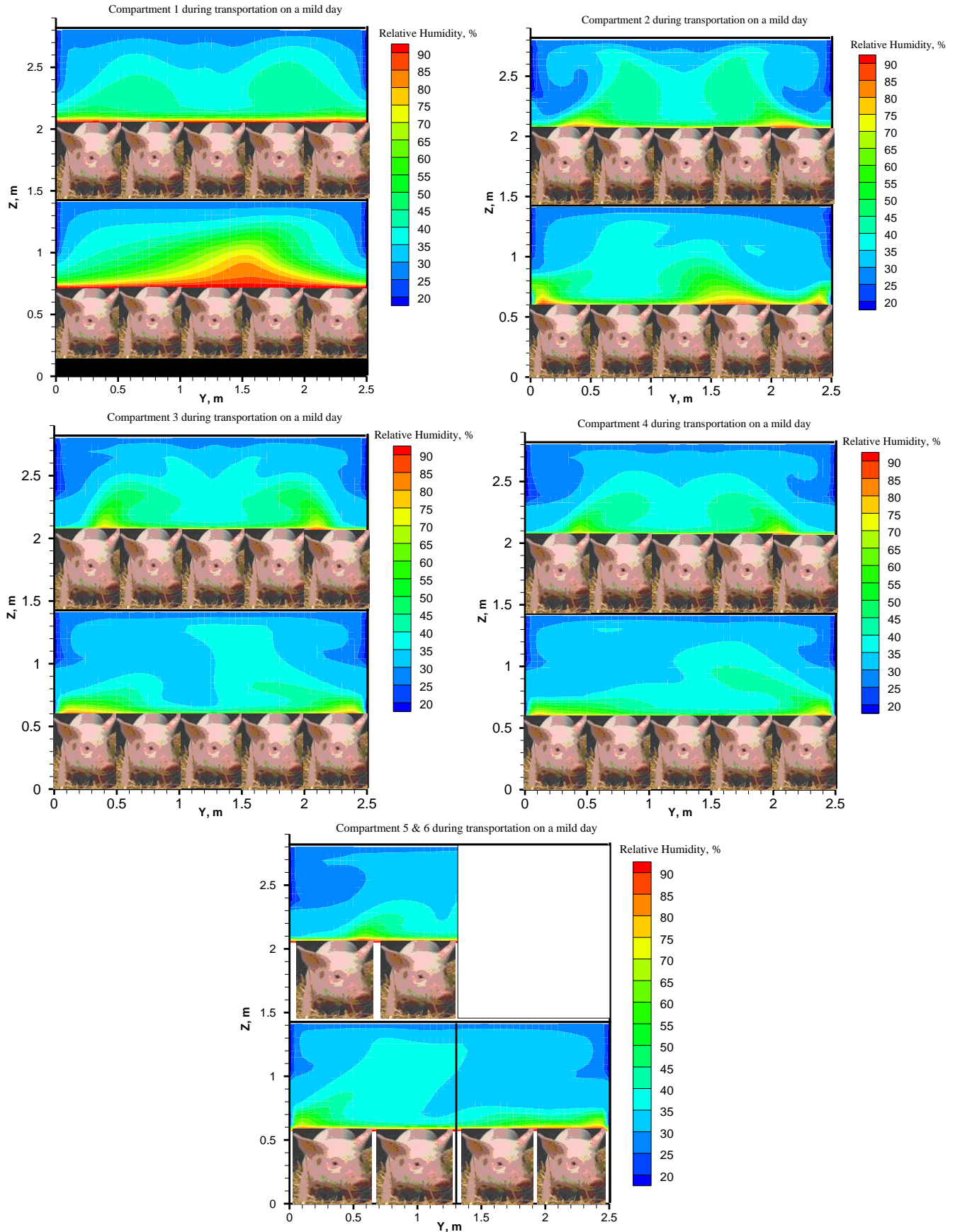


Figure C.14. Air relative humidity through the transverse sections of the trailer during transport on a cold day [Simulation 11].

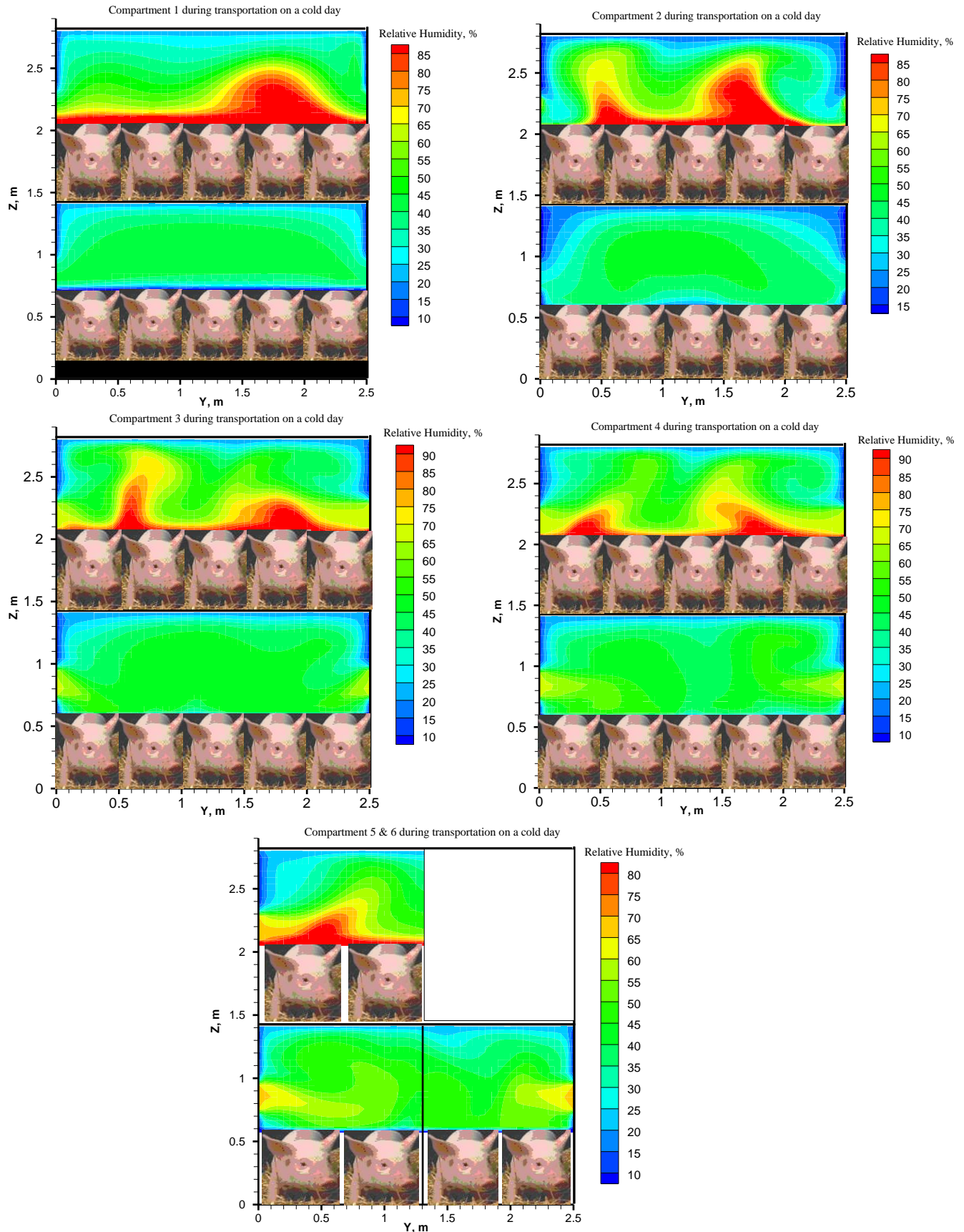


Figure C.15. Air carbon dioxide concentrations through the longitudinal sections in the center of the trailer during transport on a) hot, b) mild, c) cold days [Simulations 1, 6, and 11, respectively].

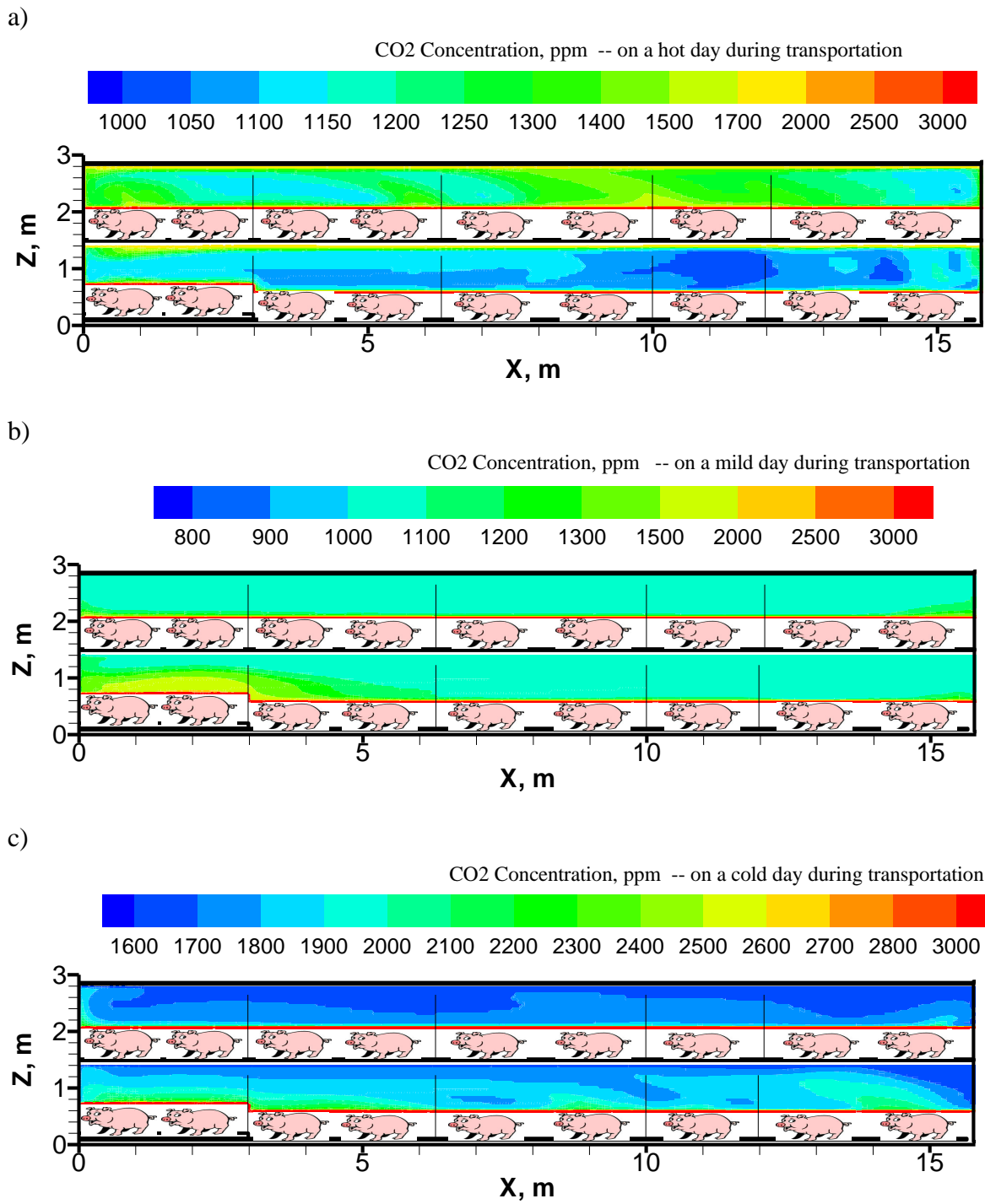


Figure C.16. Air carbon dioxide concentrations through the transverse sections of the trailer during transport on a hot day [Simulation 1].

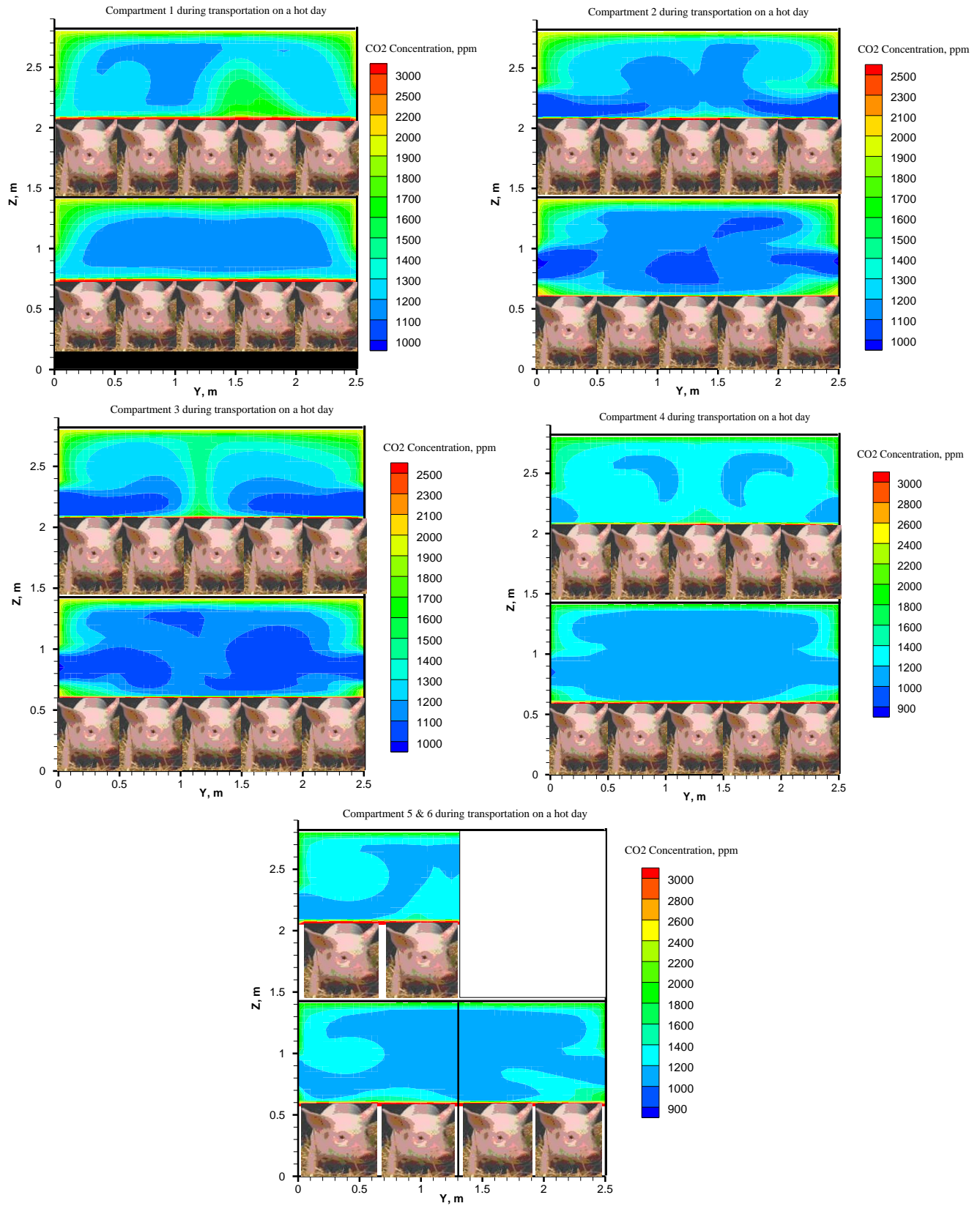


Figure C.17. Air carbon dioxide concentrations through the transverse sections of the trailer during transport on a mild day [Simulation 6].

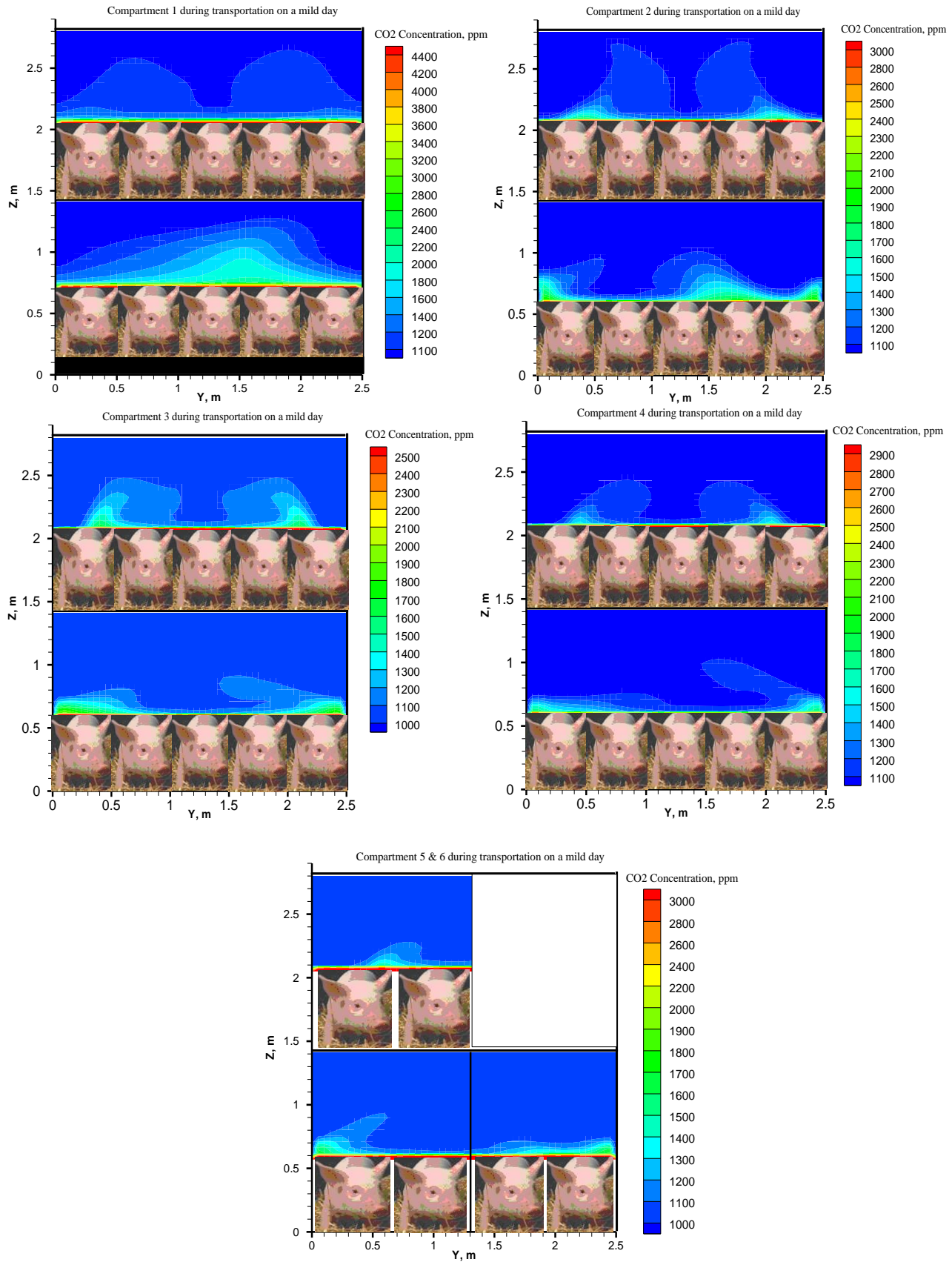


Figure C.18. Air carbon dioxide concentrations through the transverse sections of the trailer during transport on a cold day [Simulation 11].

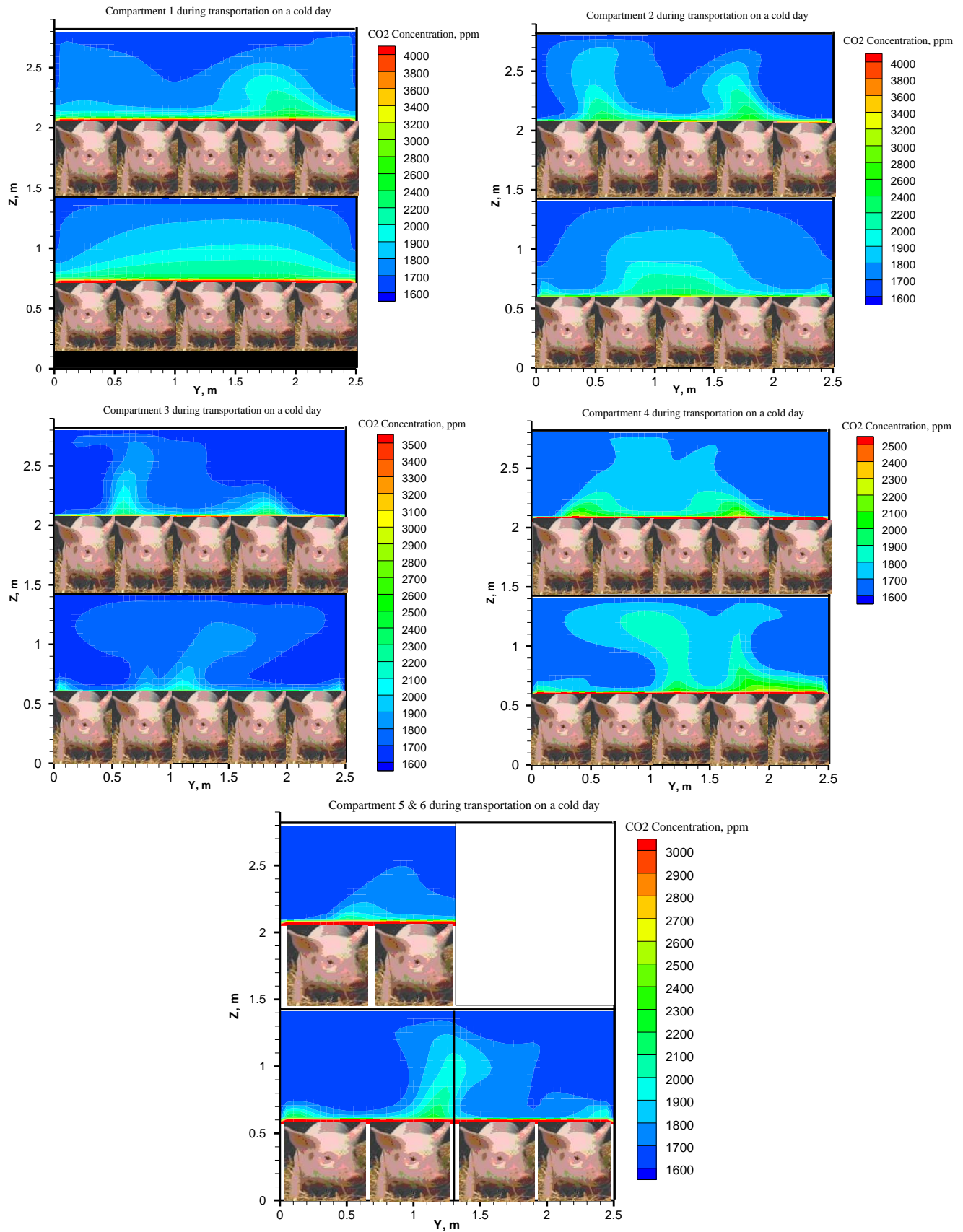


Figure C.19. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 2, 7, and 12, respectively].

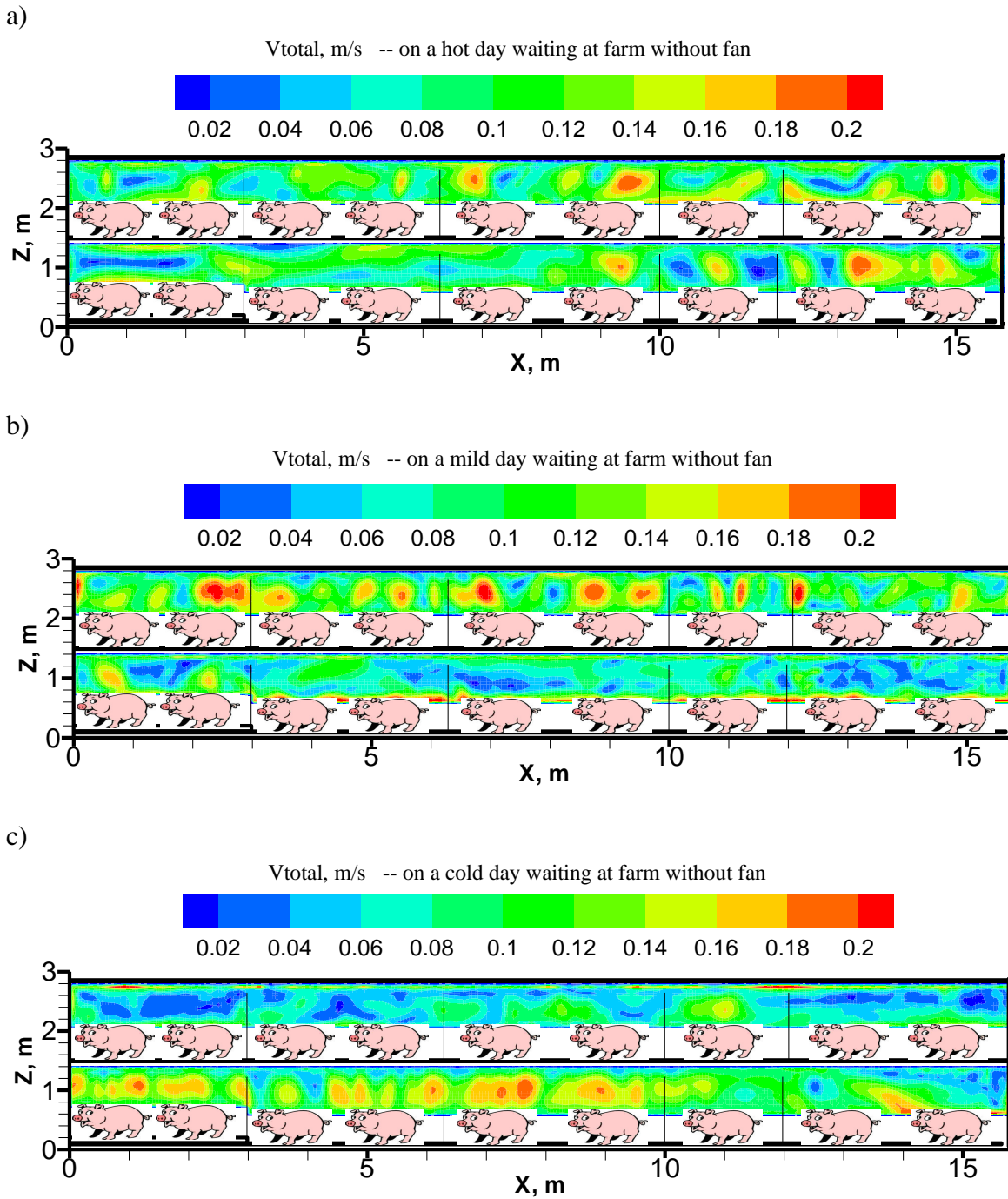
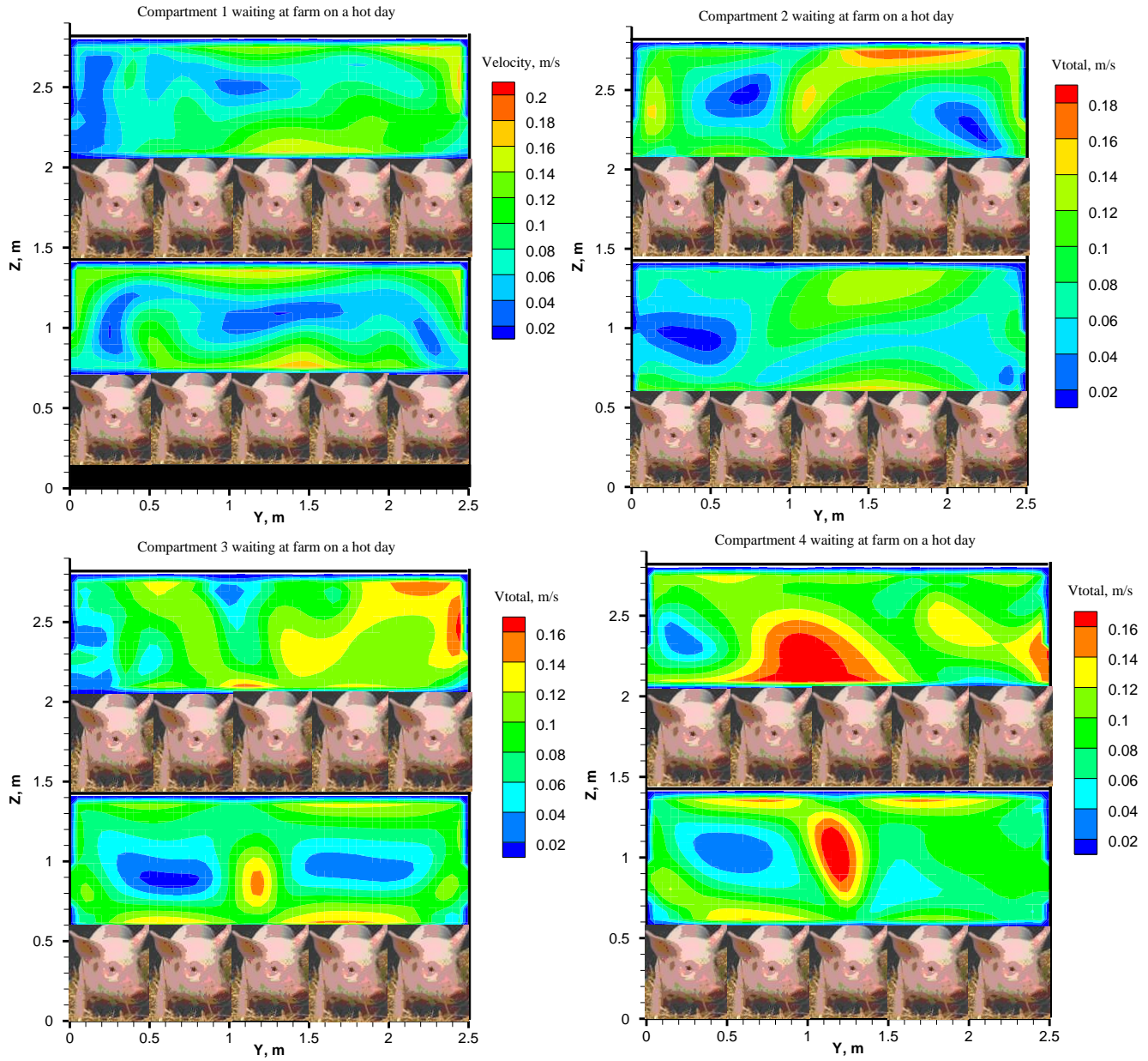


Figure C.20. Air velocity through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a hot day – without any external fans operating [Simulation 2].



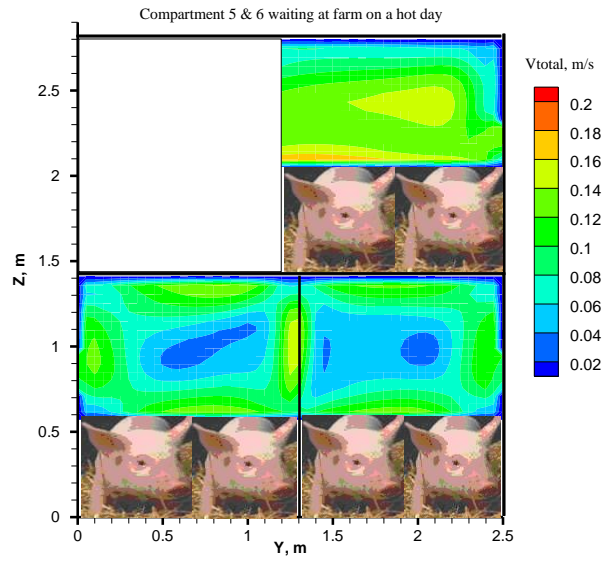
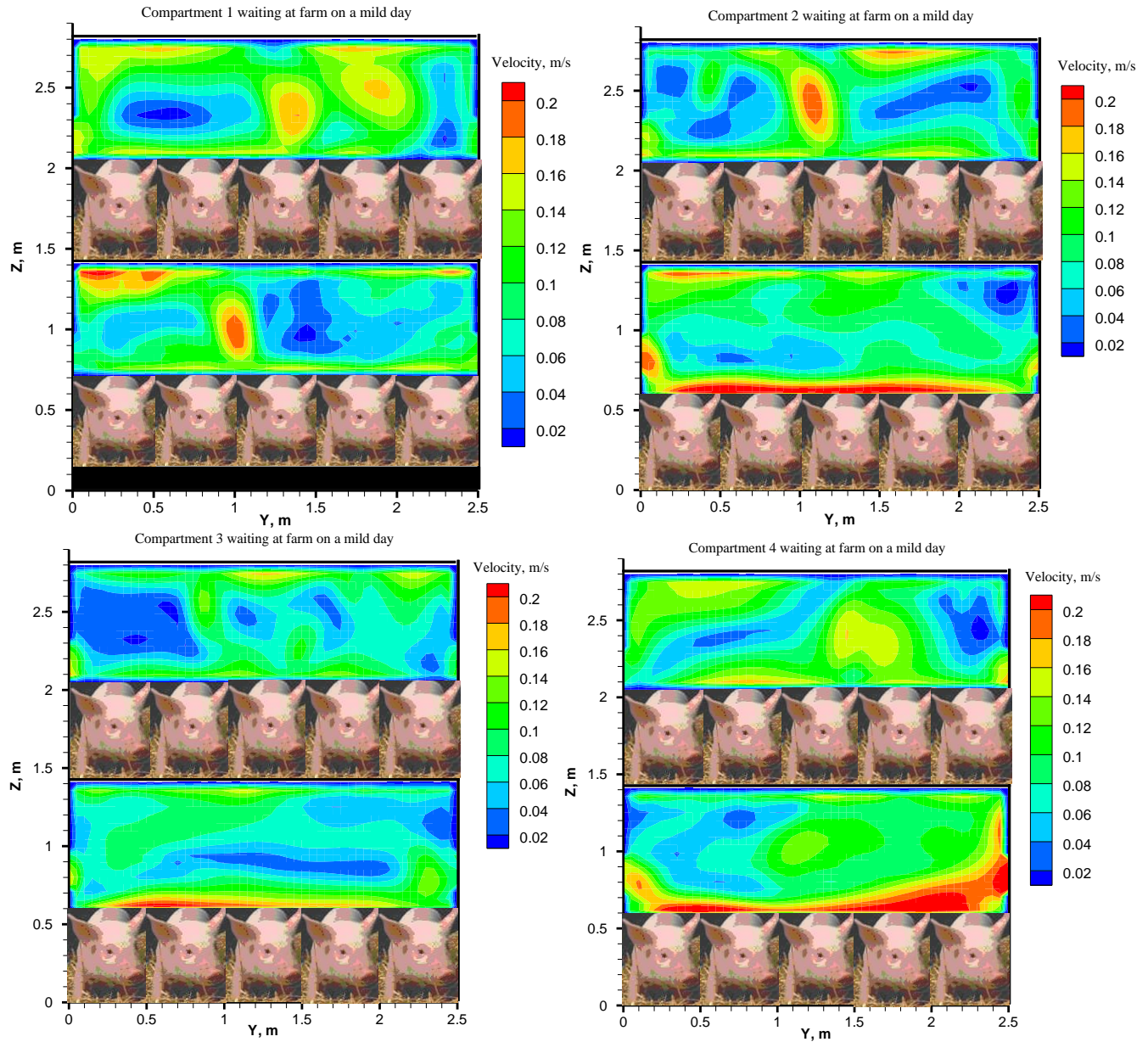


Figure C.21. Air velocity through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a mild day – without any external fans operating [Simulation 7].



Compartment 5 & 6 waiting at farm on a mild day

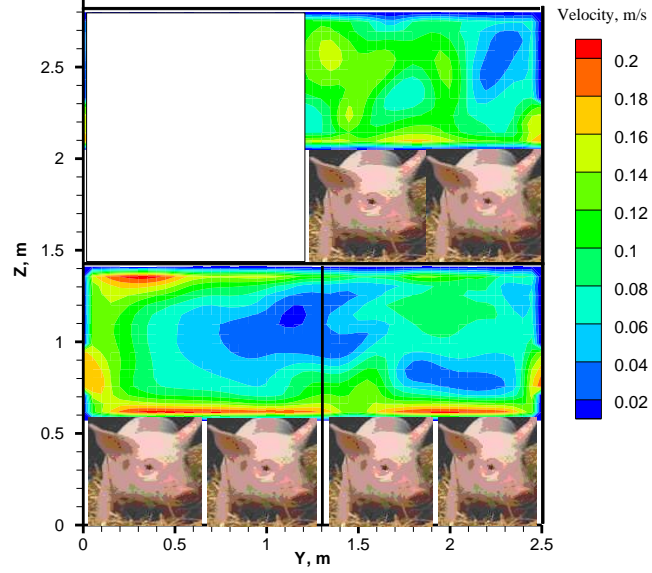
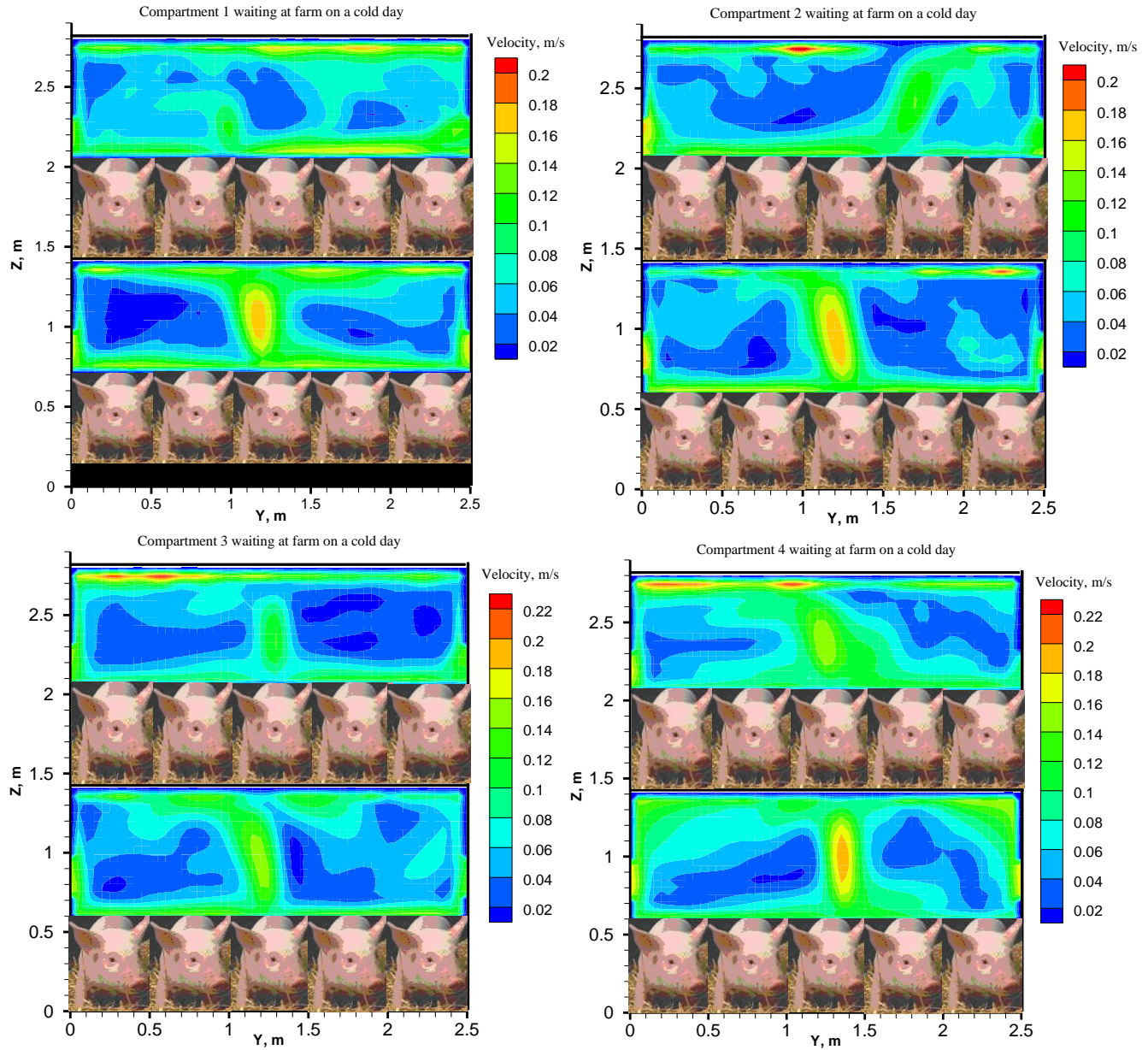


Figure C.22. Air velocity through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a cold day – without any external fans operating [Simulation 12].



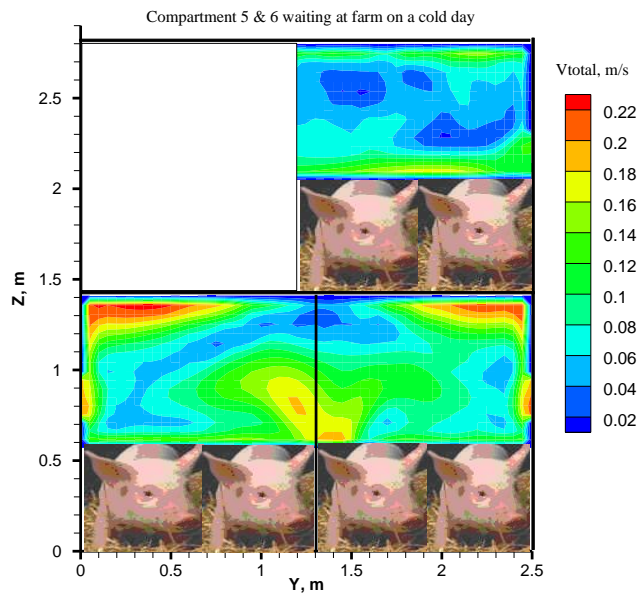


Figure C.23. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 2, 7, and 12, respectively].

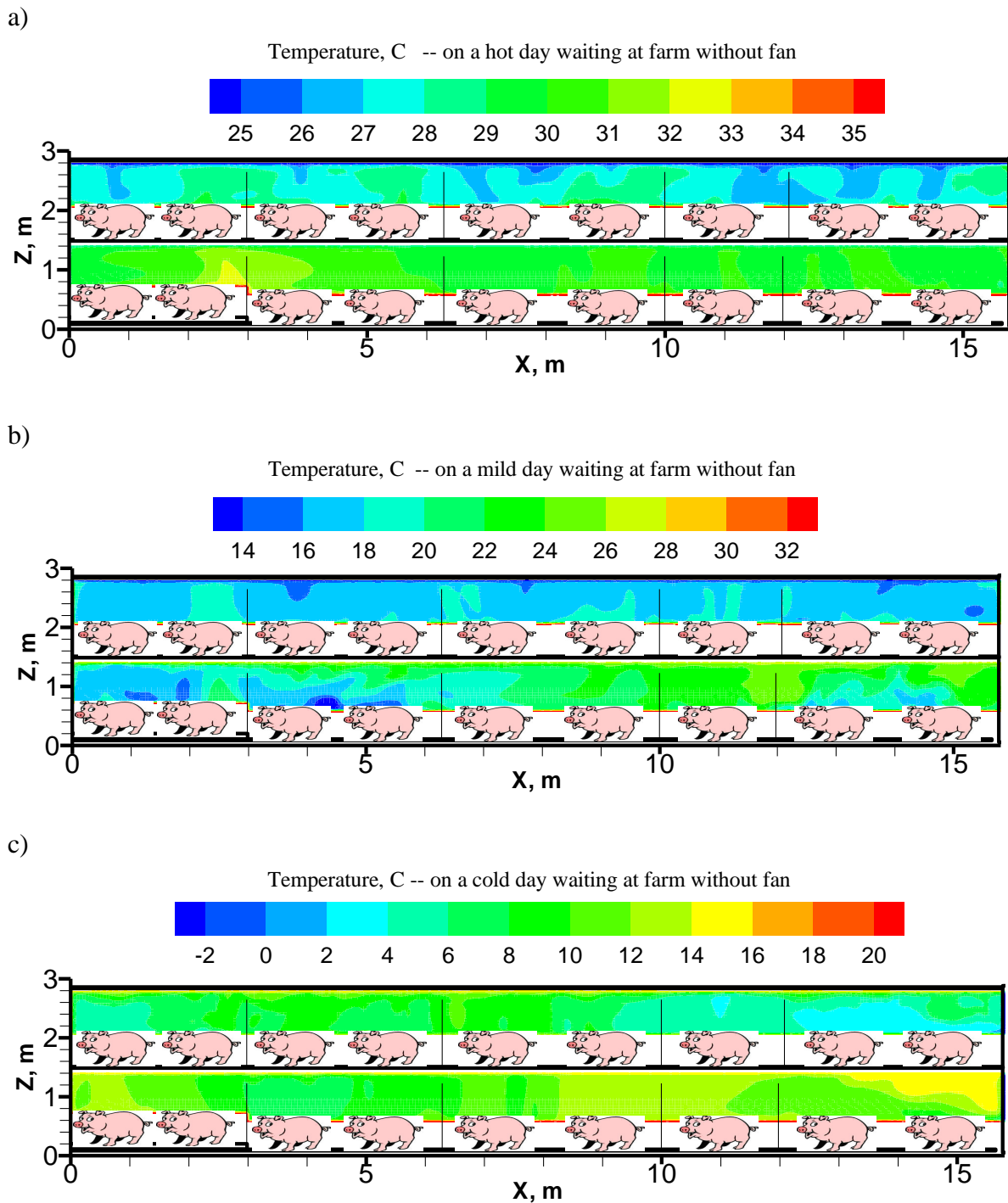
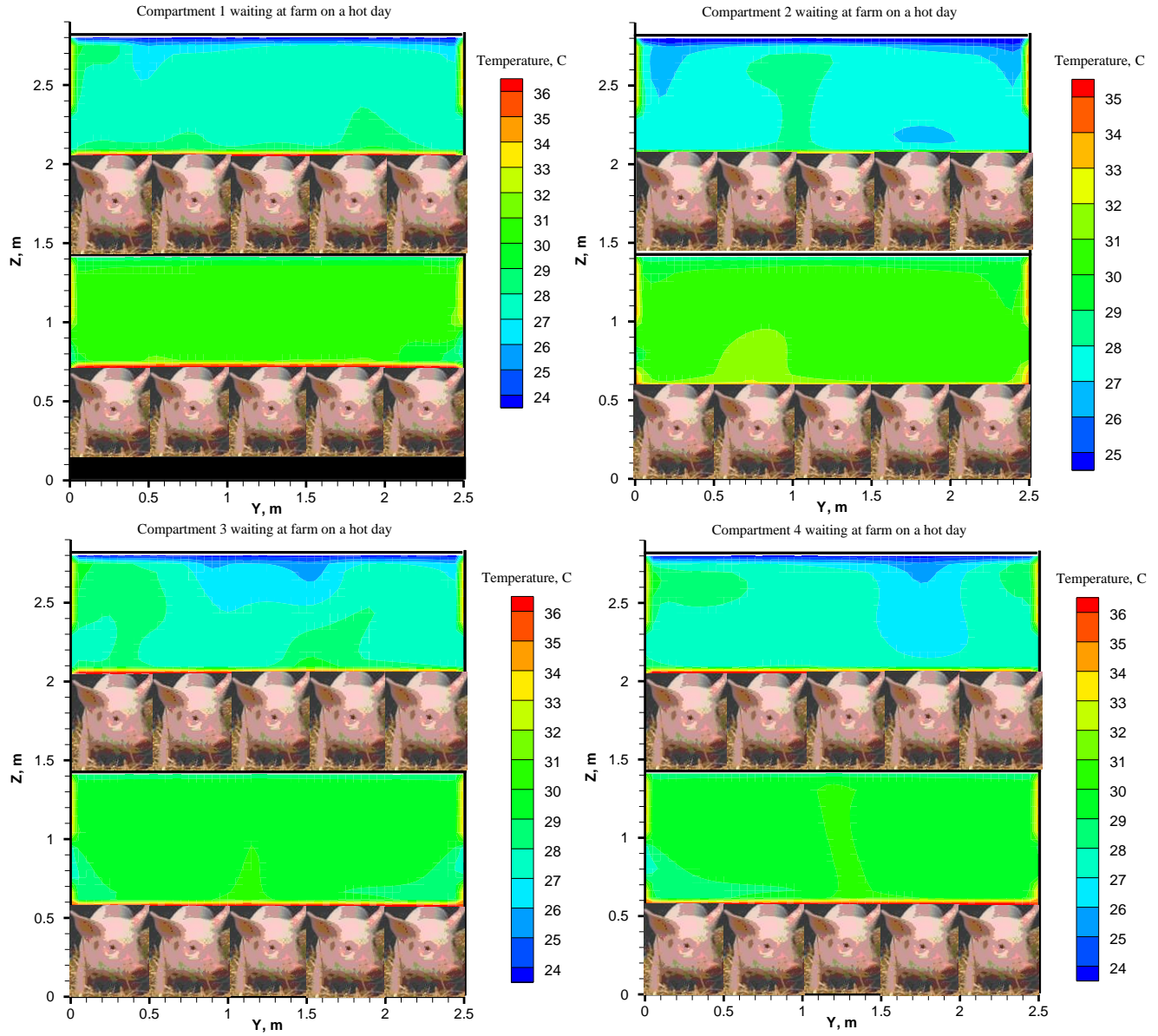


Figure C.24. Air temperature through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a hot day – without any external fans operating [Simulation 2].



Compartment 5 & 6 waiting at farm on a hot day

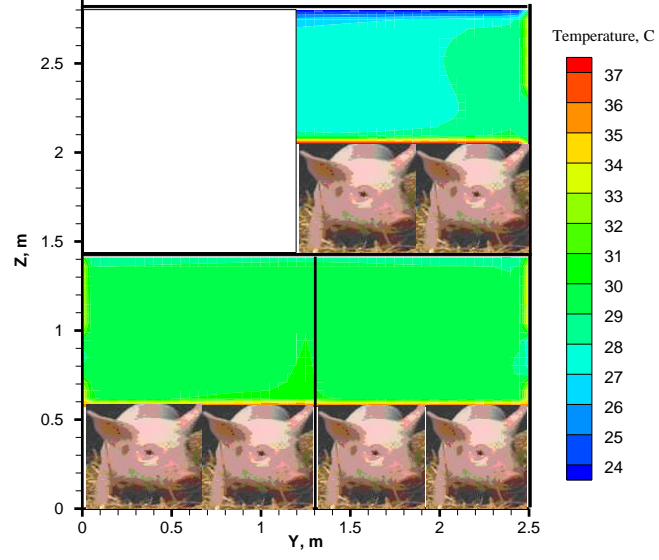
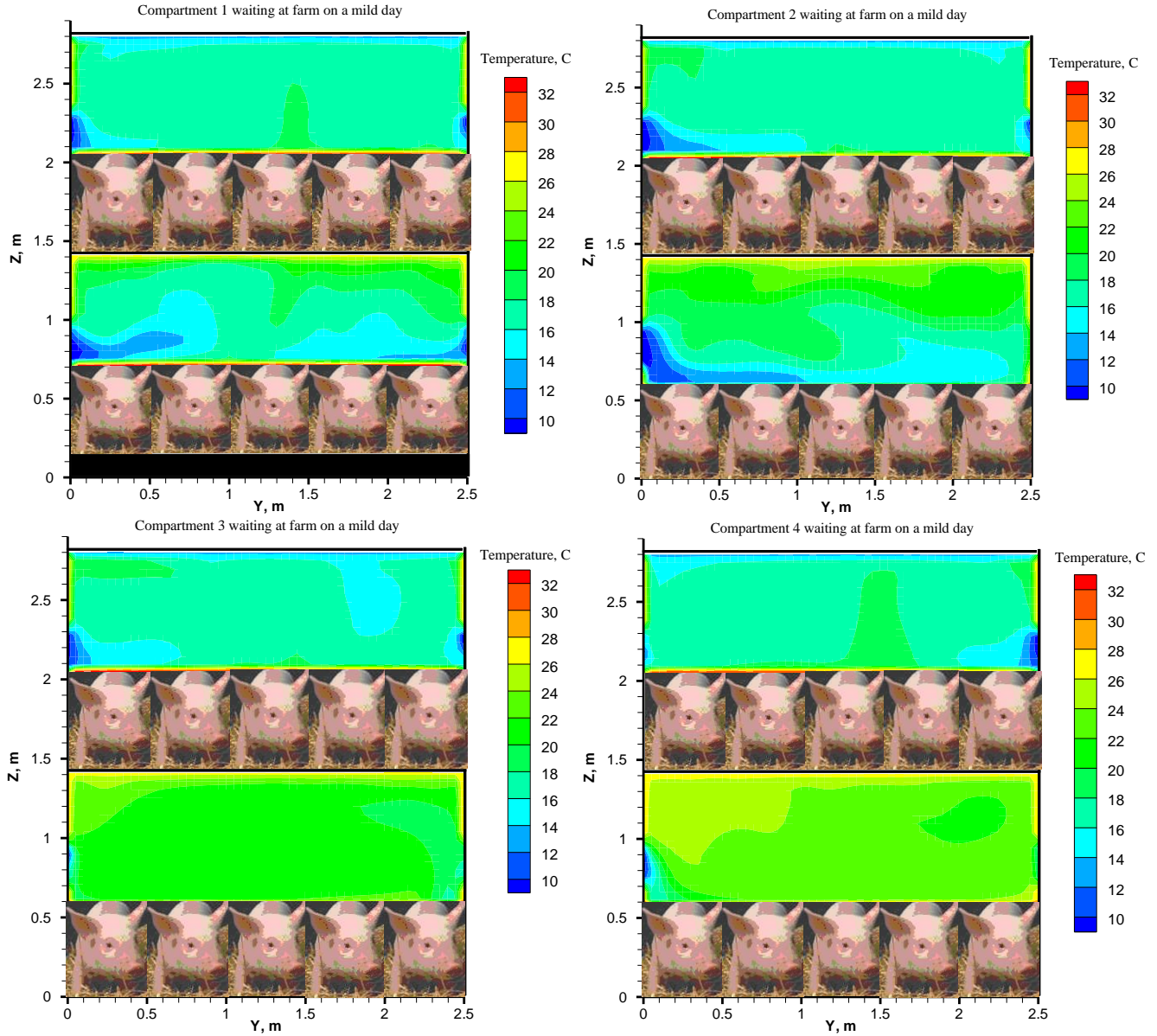


Figure C.25. Air temperature through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a mild day – without any external fans operating [Simulation 7].



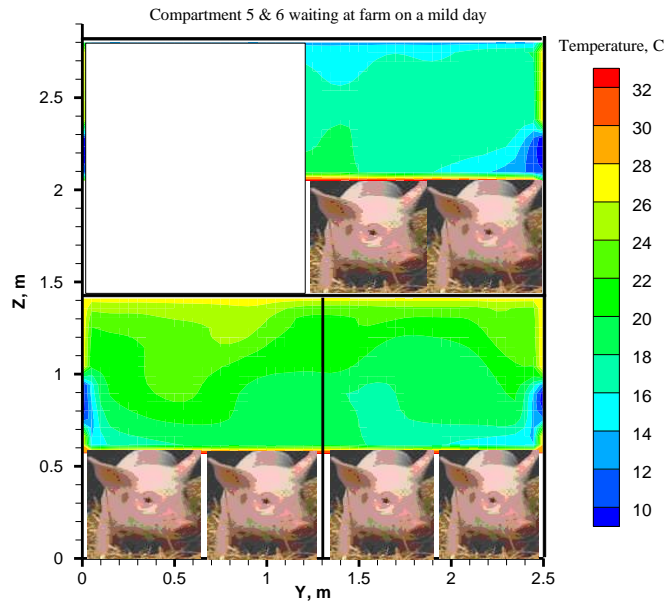
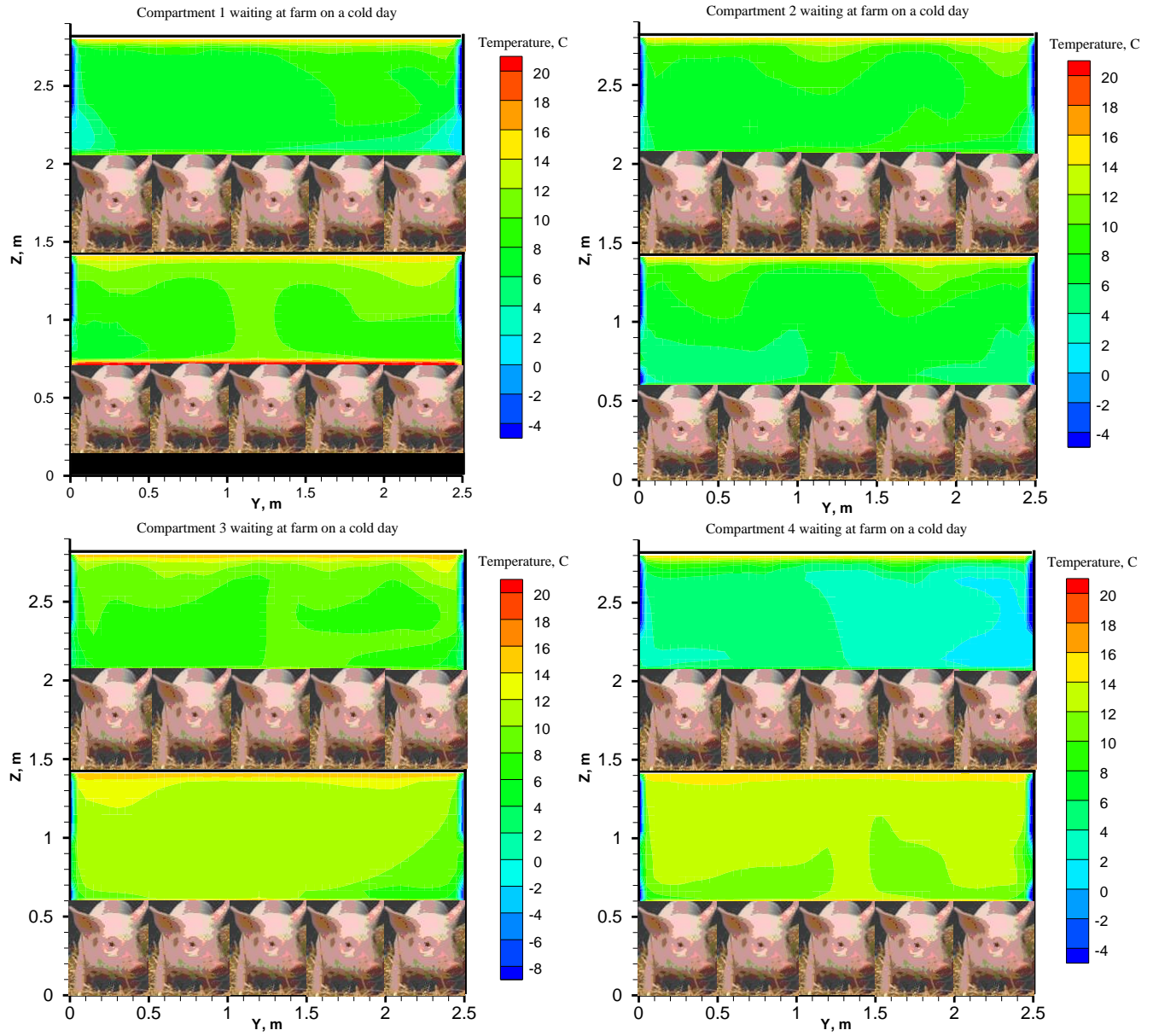


Figure C.26. Air temperature through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a cold day – without any external fans operating [Simulation 12].



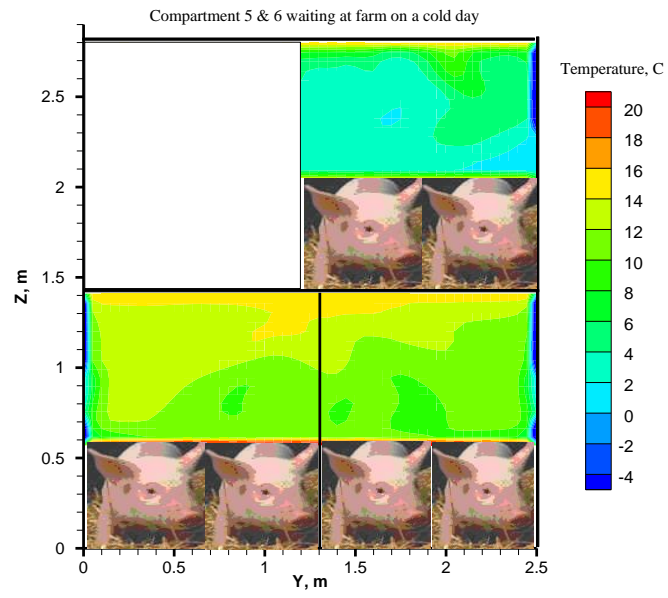


Figure C.27. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 2, 7, and 12, respectively].

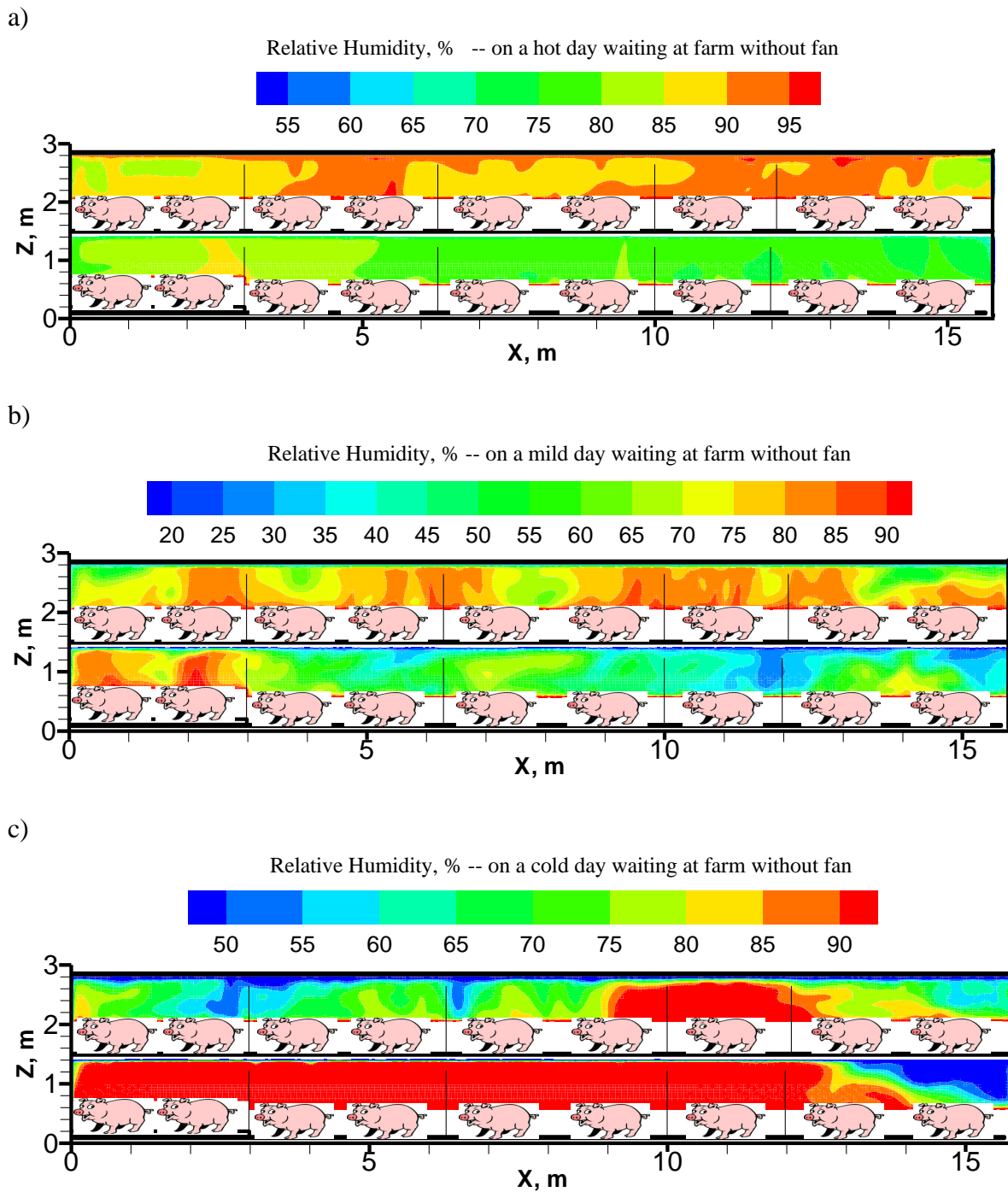


Figure C.28. Air relative humidity through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a hot day – without any external fans operating [Simulation 2].

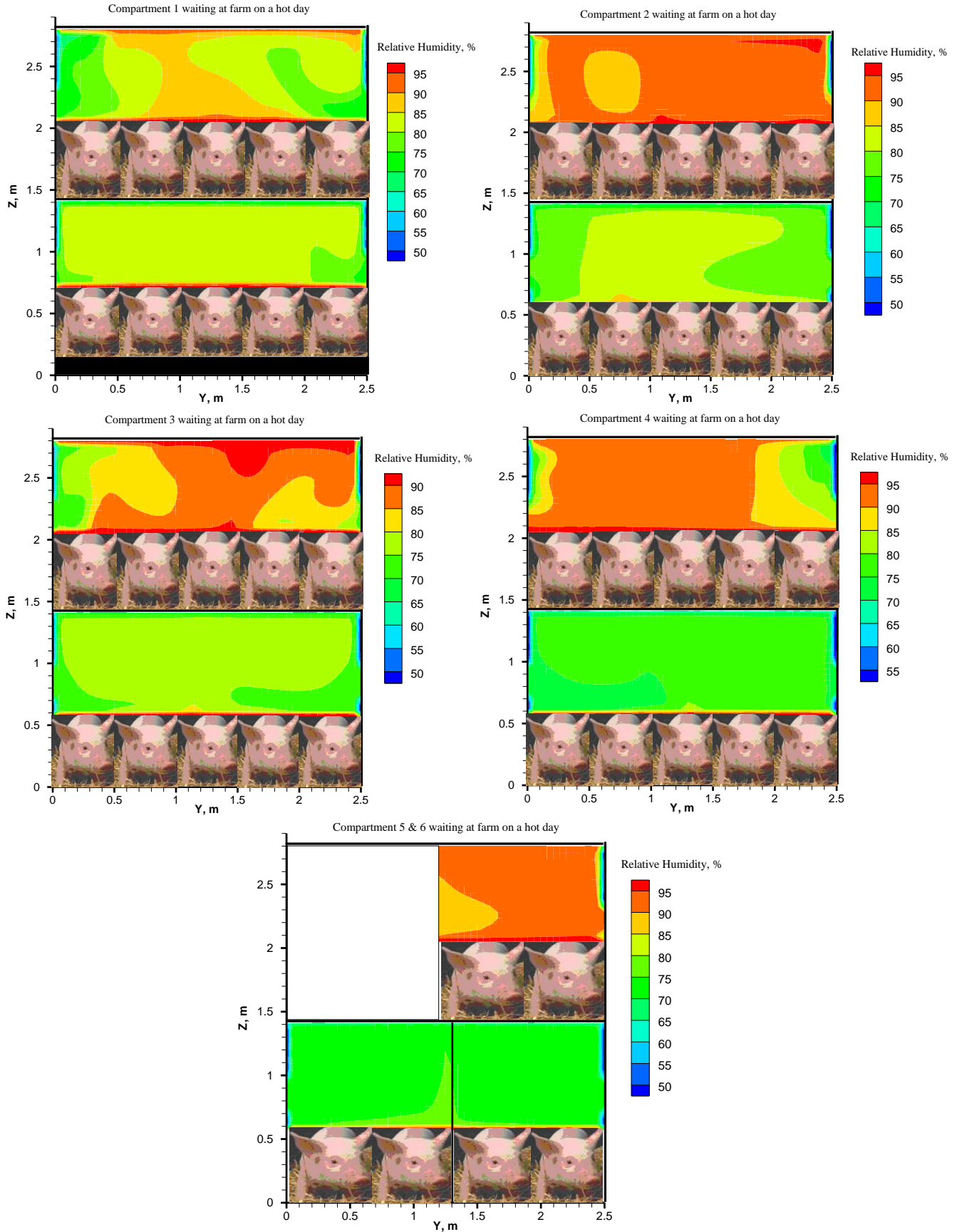


Figure C.29. Air relative humidity through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a mild day – without any external fans operating [Simulation 7].

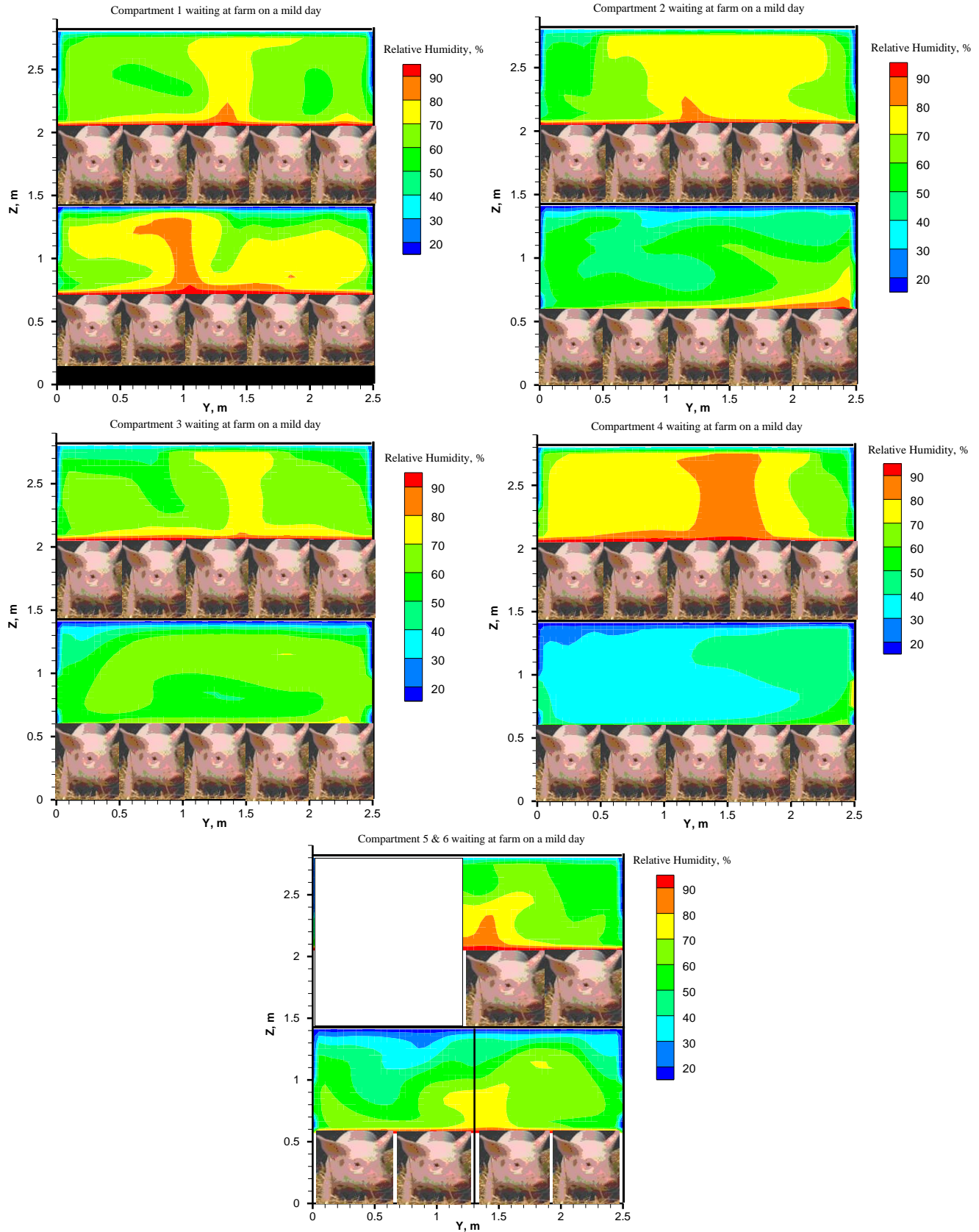


Figure C.30. Air relative humidity through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a cold day – without any external fans operating [Simulation 12].

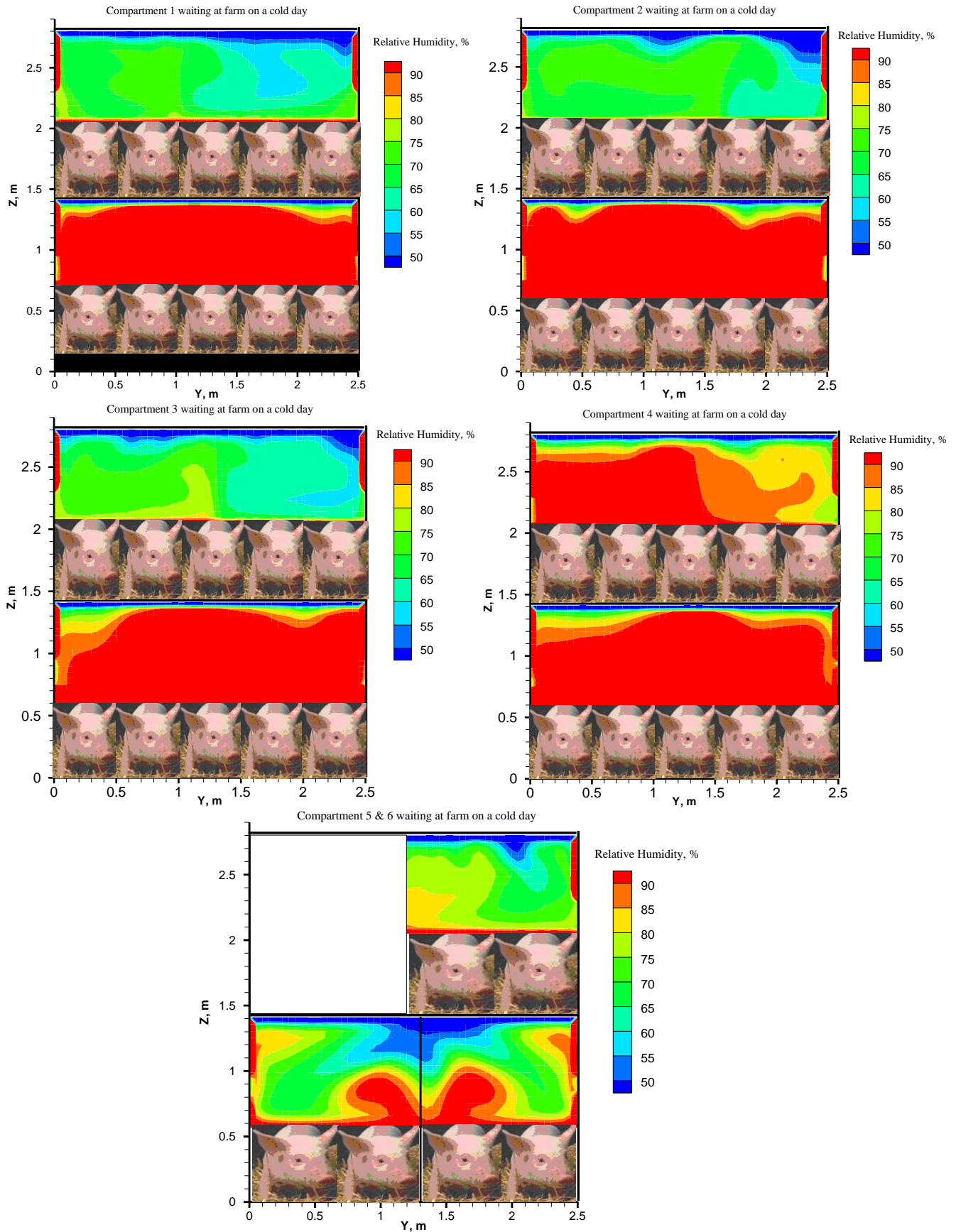


Figure C.31. Air carbon dioxide concentration through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 2, 7, and 12, respectively].

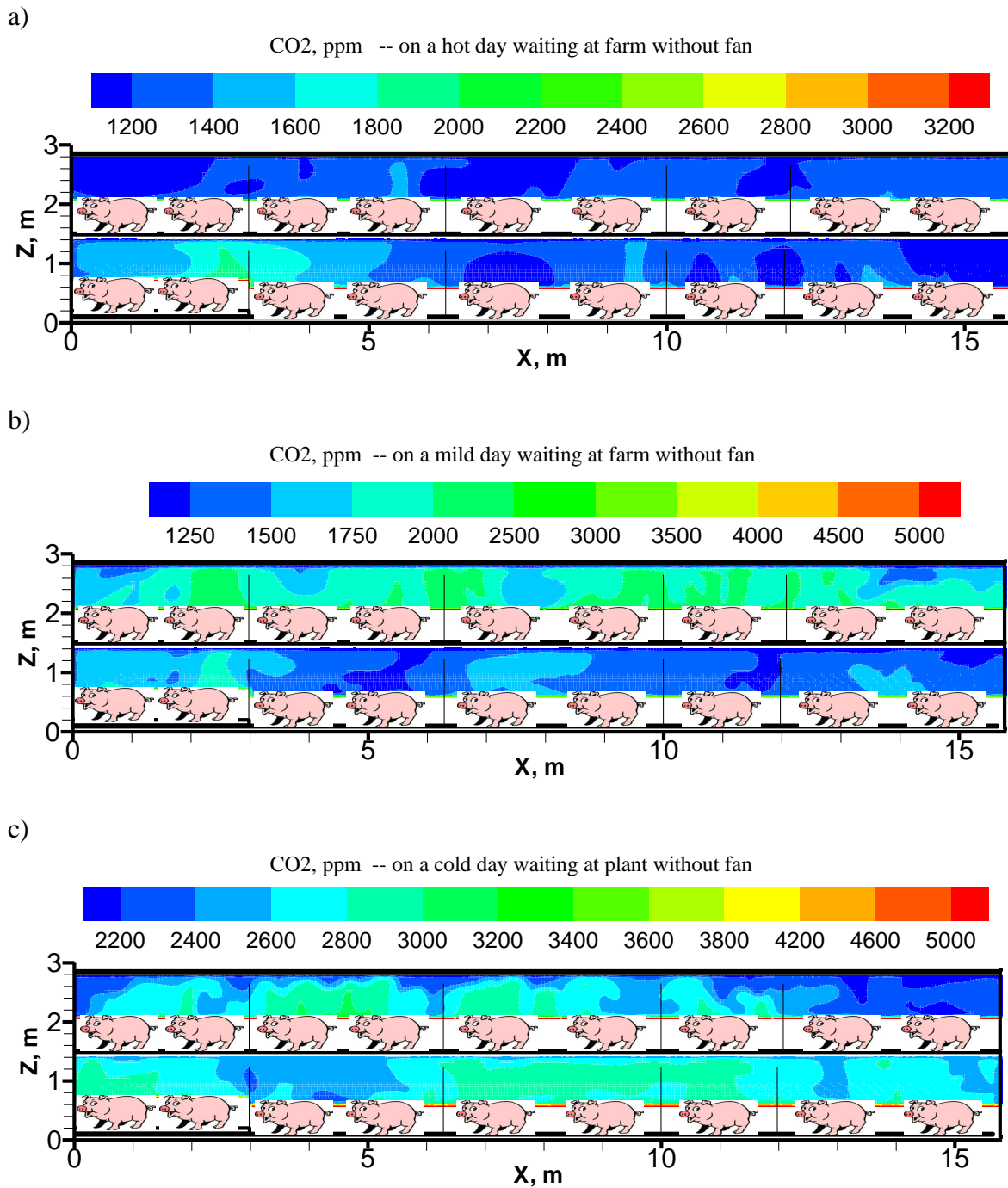
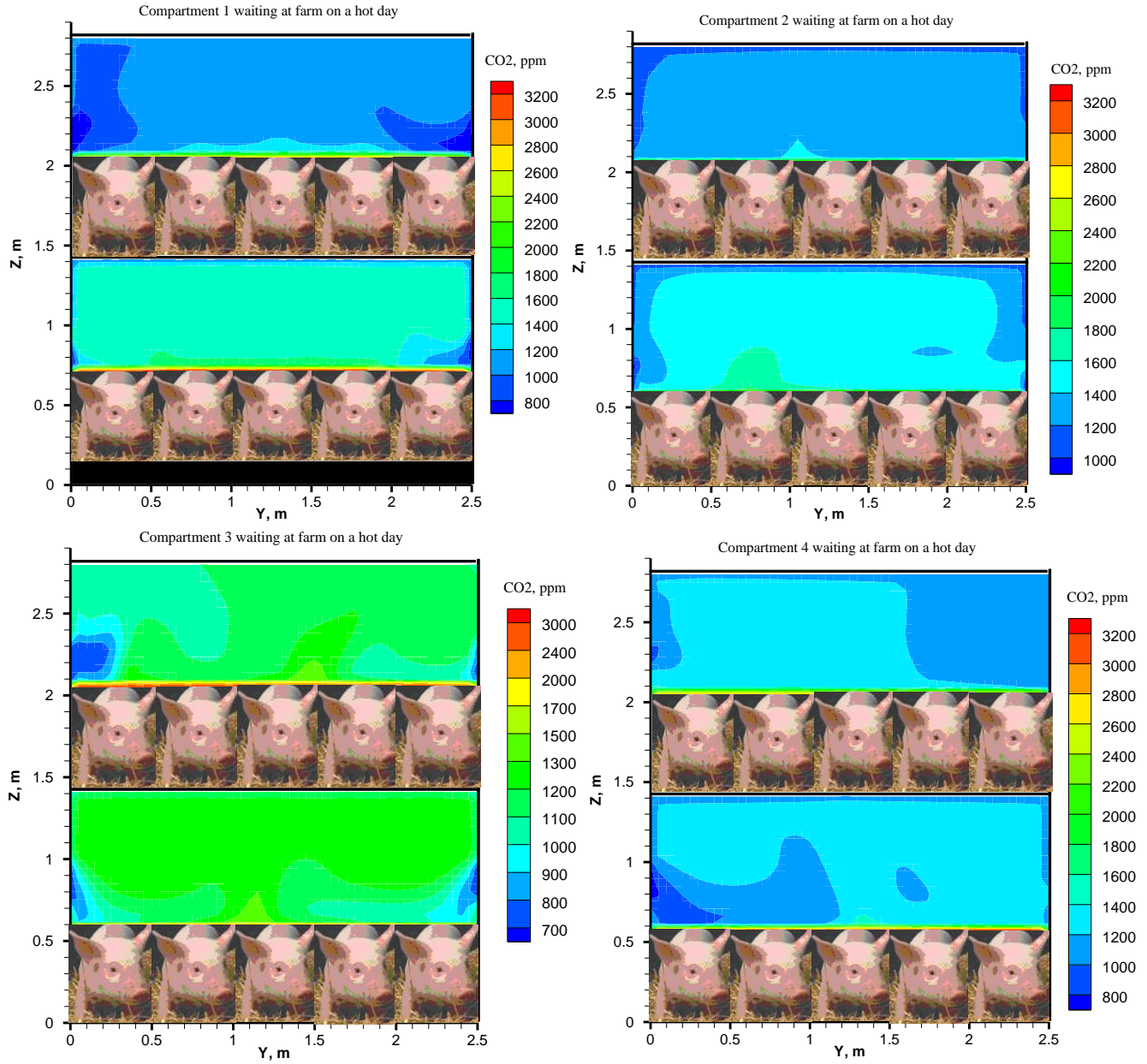


Figure C.32. Air carbon dioxide concentration through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a hot day – without any external fans operating [Simulation 2].



Compartment 5 & 6 waiting at farm on a hot day

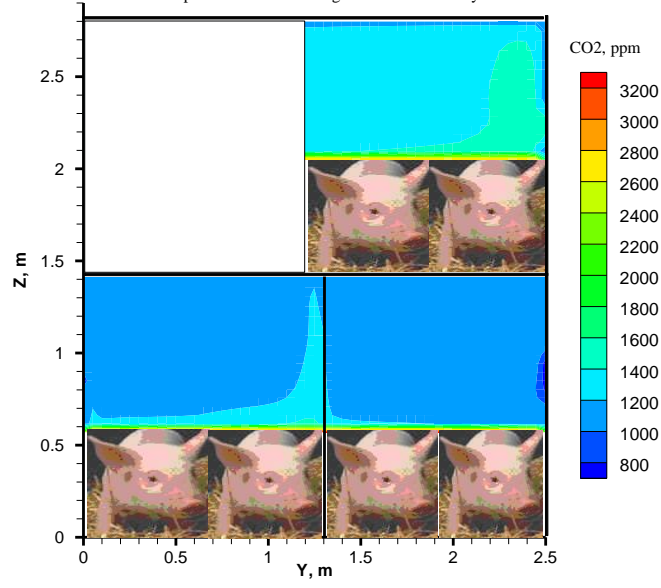
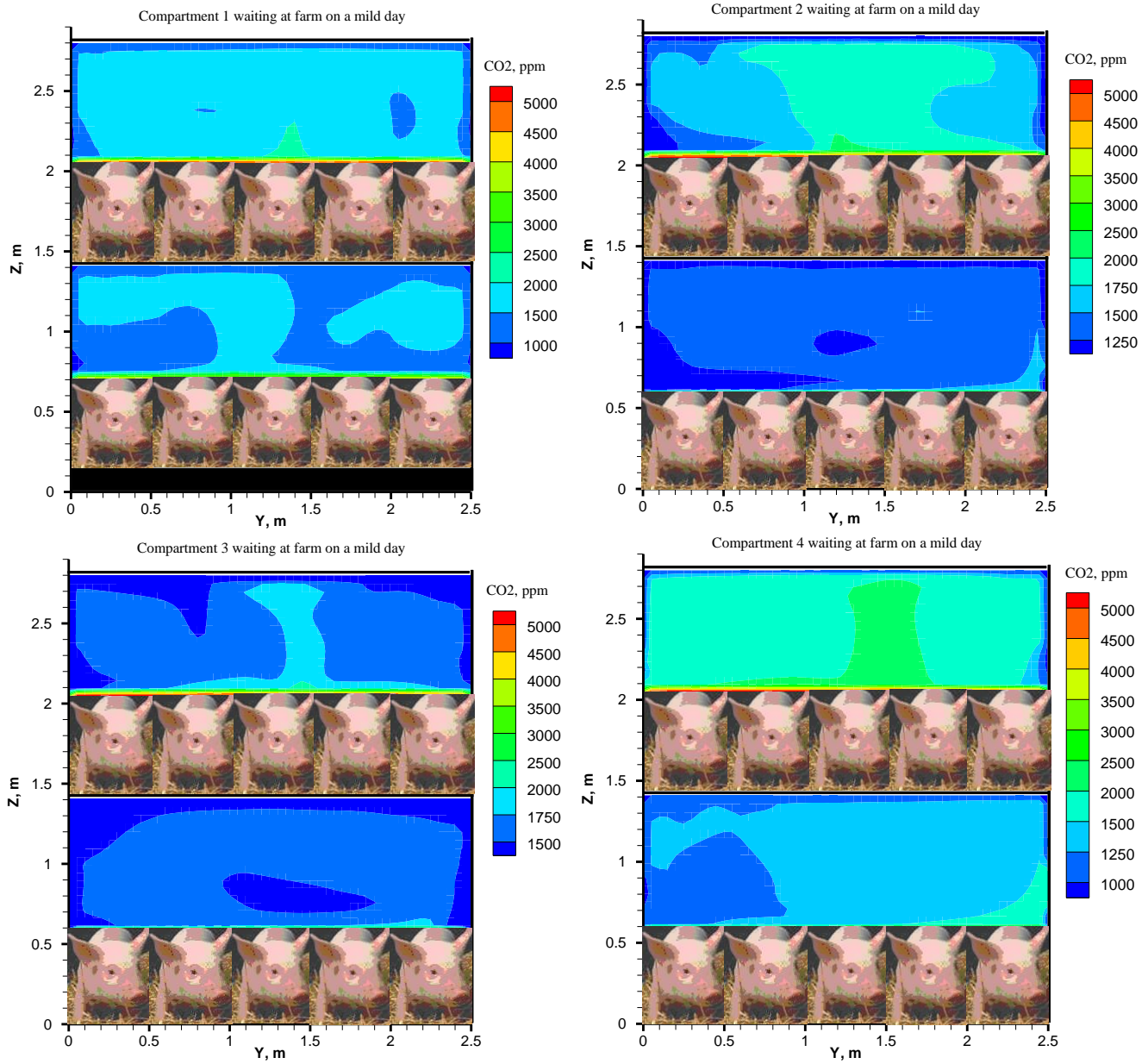


Figure C.33. Air carbon dioxide concentration through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a mild day – without any external fans operating [Simulation 7].



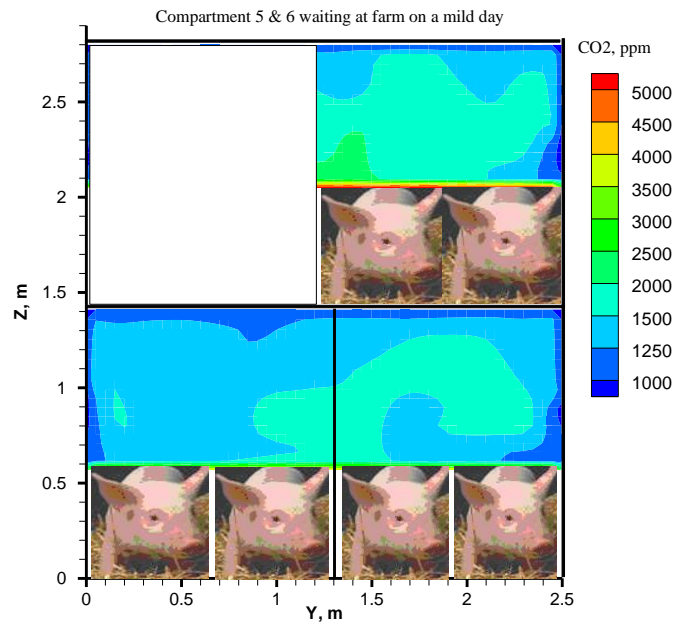
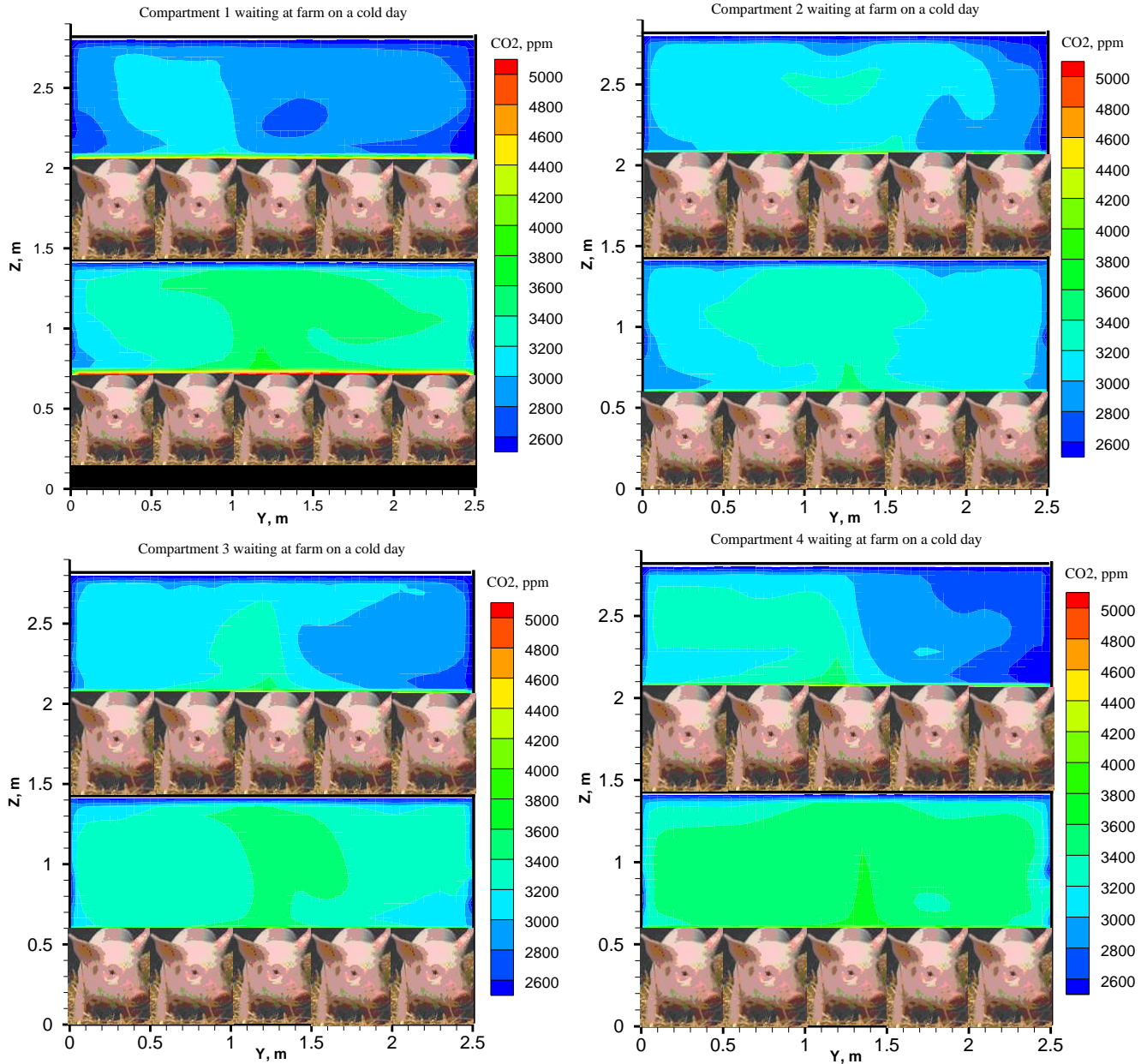


Figure C.34. Air carbon dioxide concentration through the transverse sections of the trailer during the period the trailer was standing, waiting at the farm on a cold day – without any external fans operating [Simulation 12].



Compartment 5 & 6 waiting at farm on a cold day

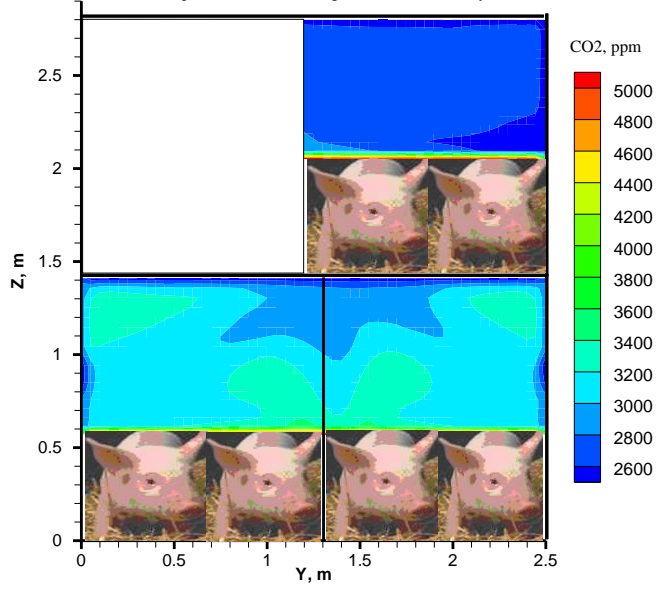


Figure C.35. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 3, 8, and 13, respectively].

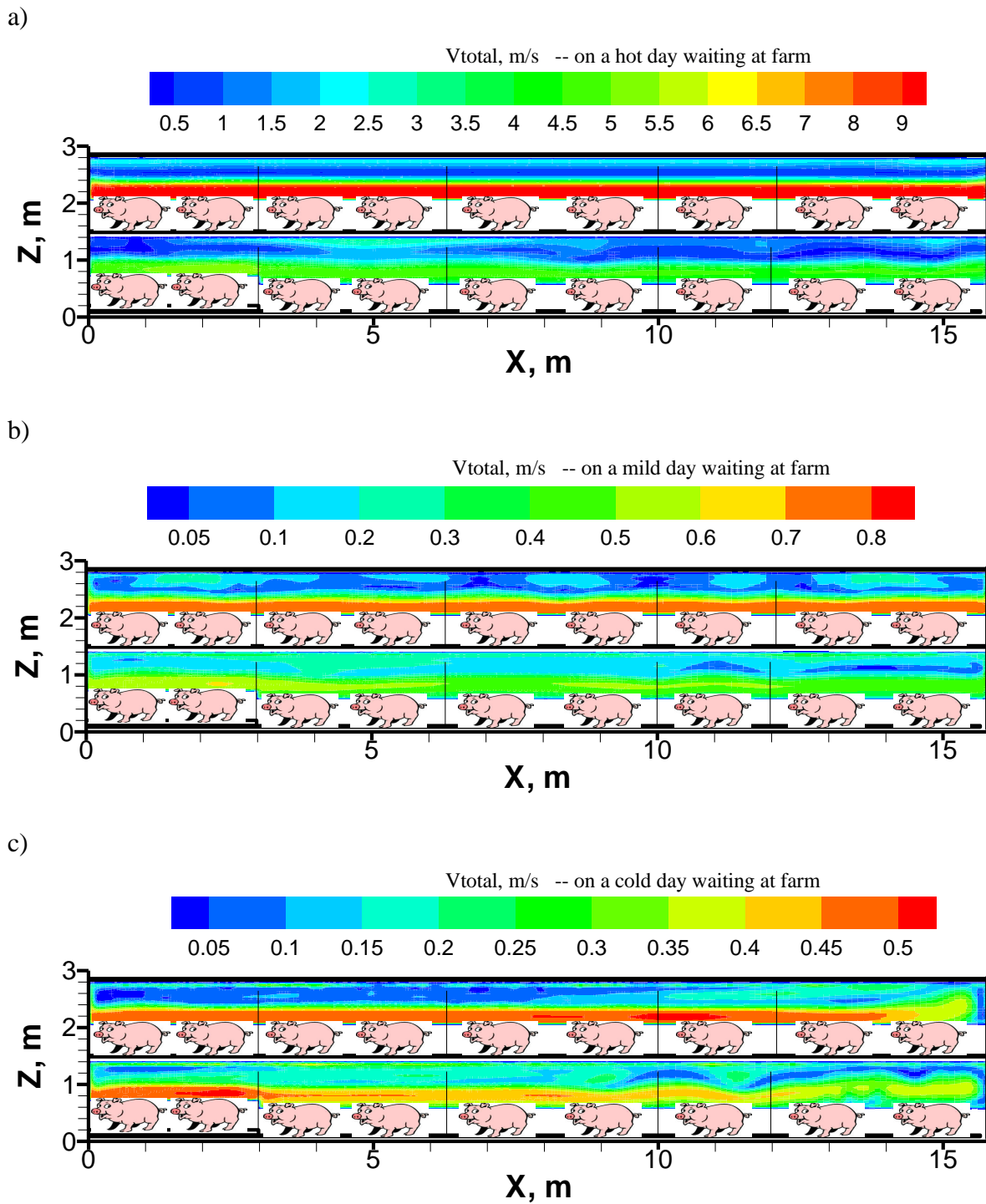


Figure C.36. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 3, 8, and 13, respectively].

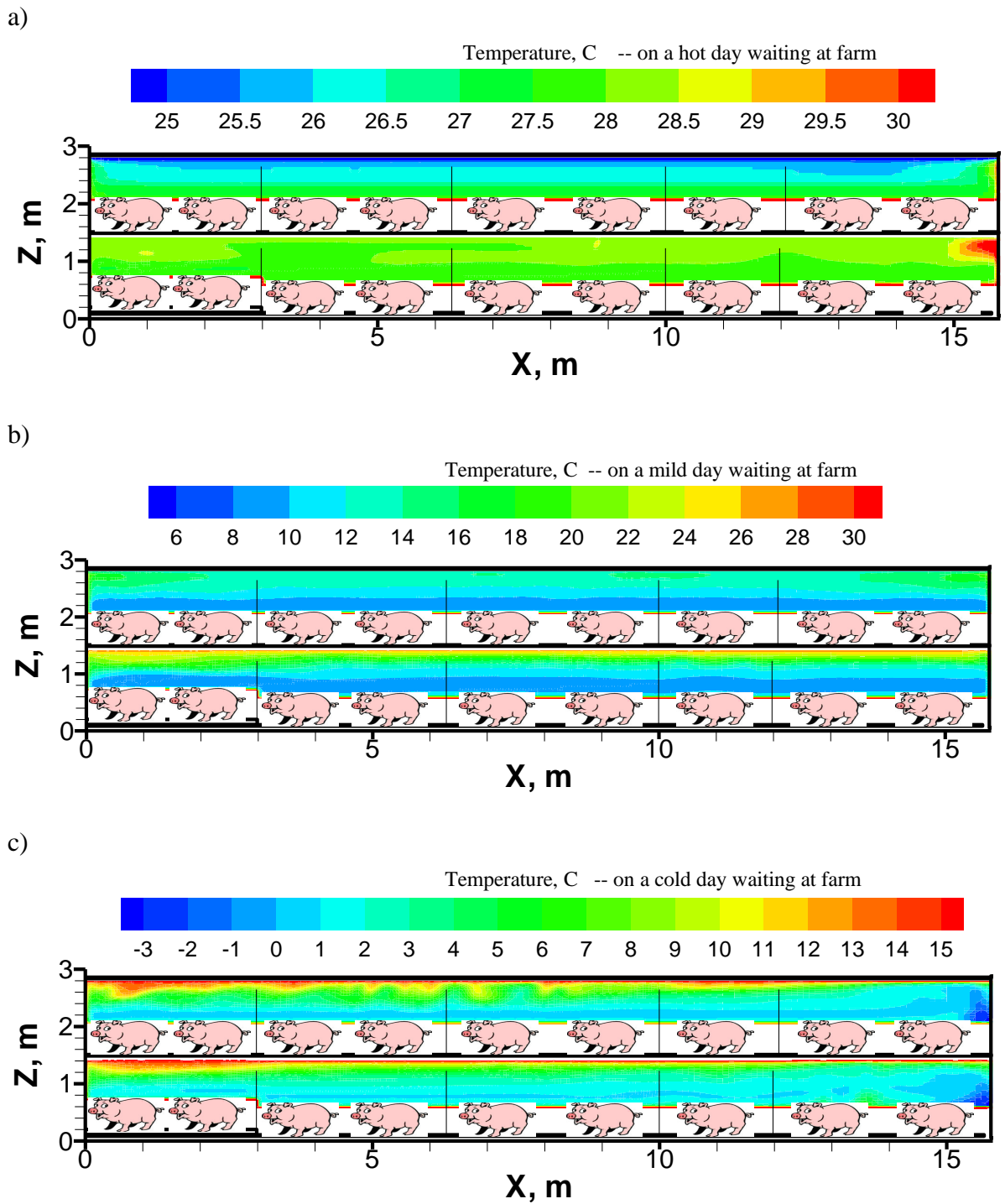


Figure C.37. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 3, 8, and 13, respectively].

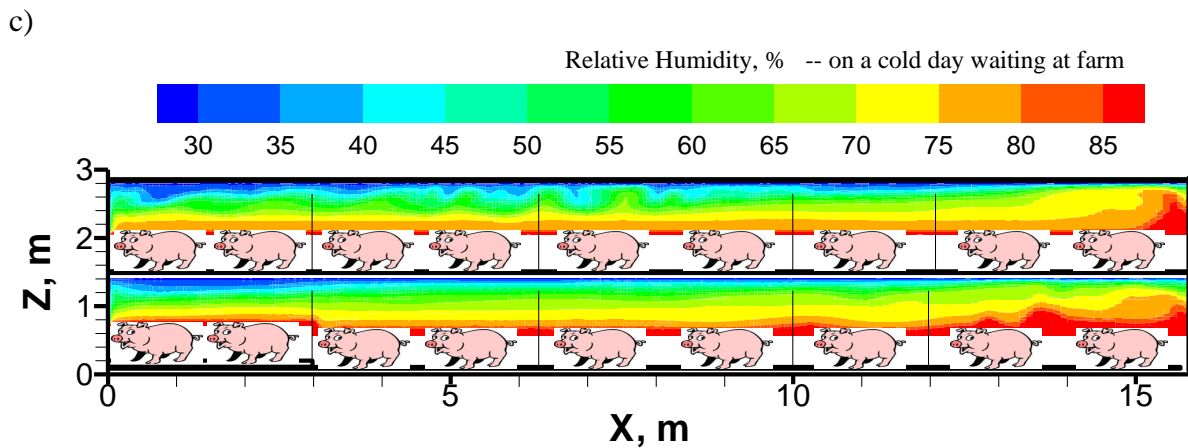
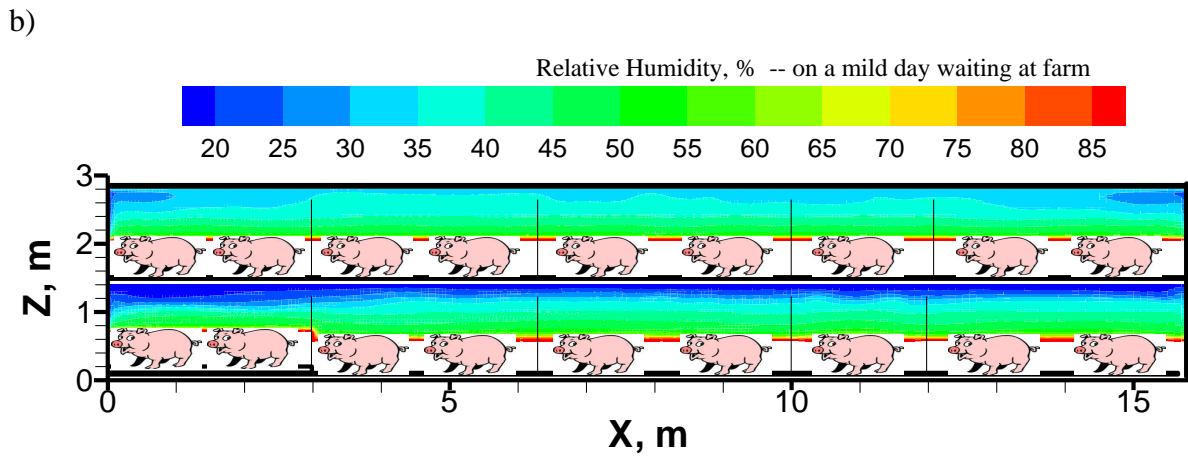
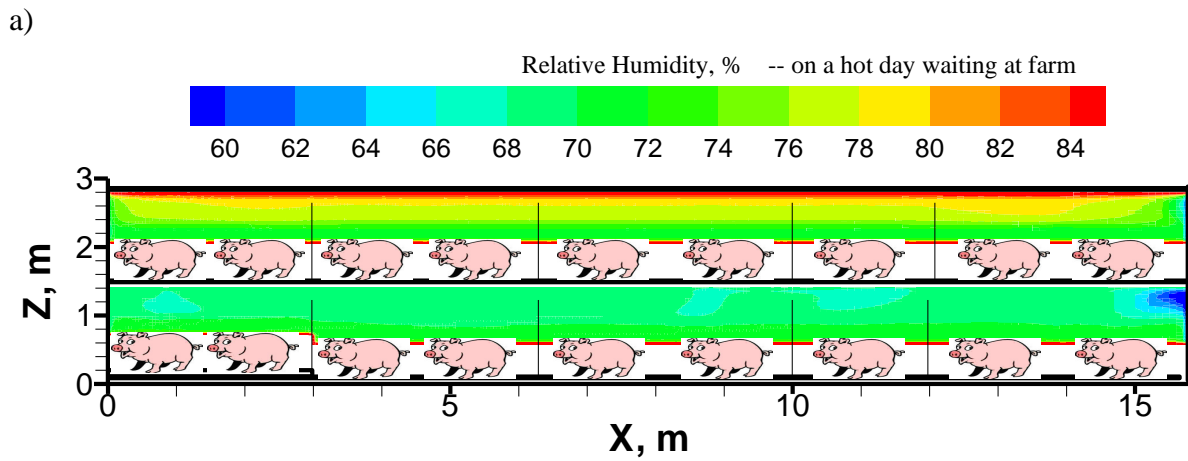


Figure C.38. Air carbon dioxide concentration through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the farm on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 3, 8, and 13, respectively].

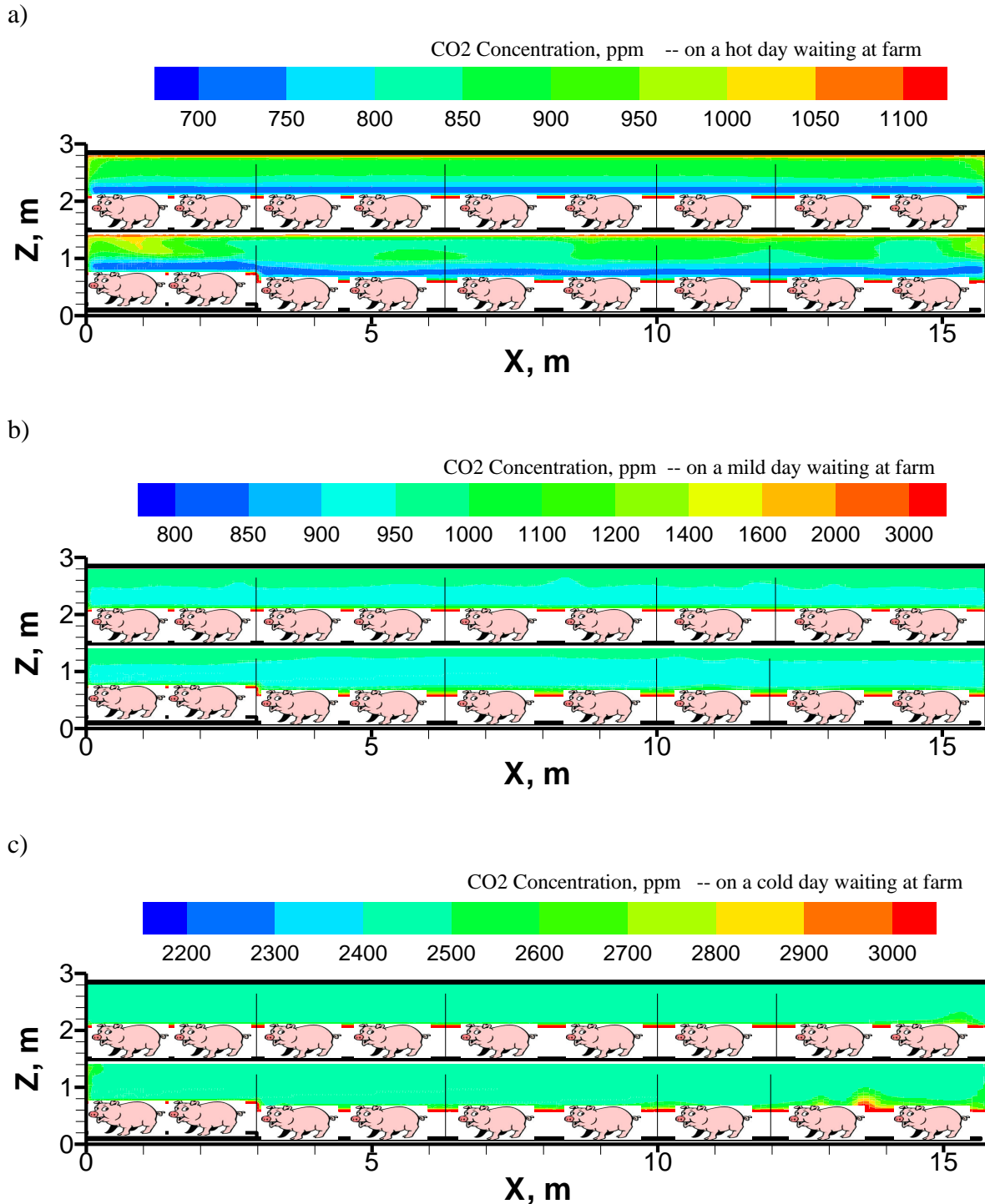


Figure C.39. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

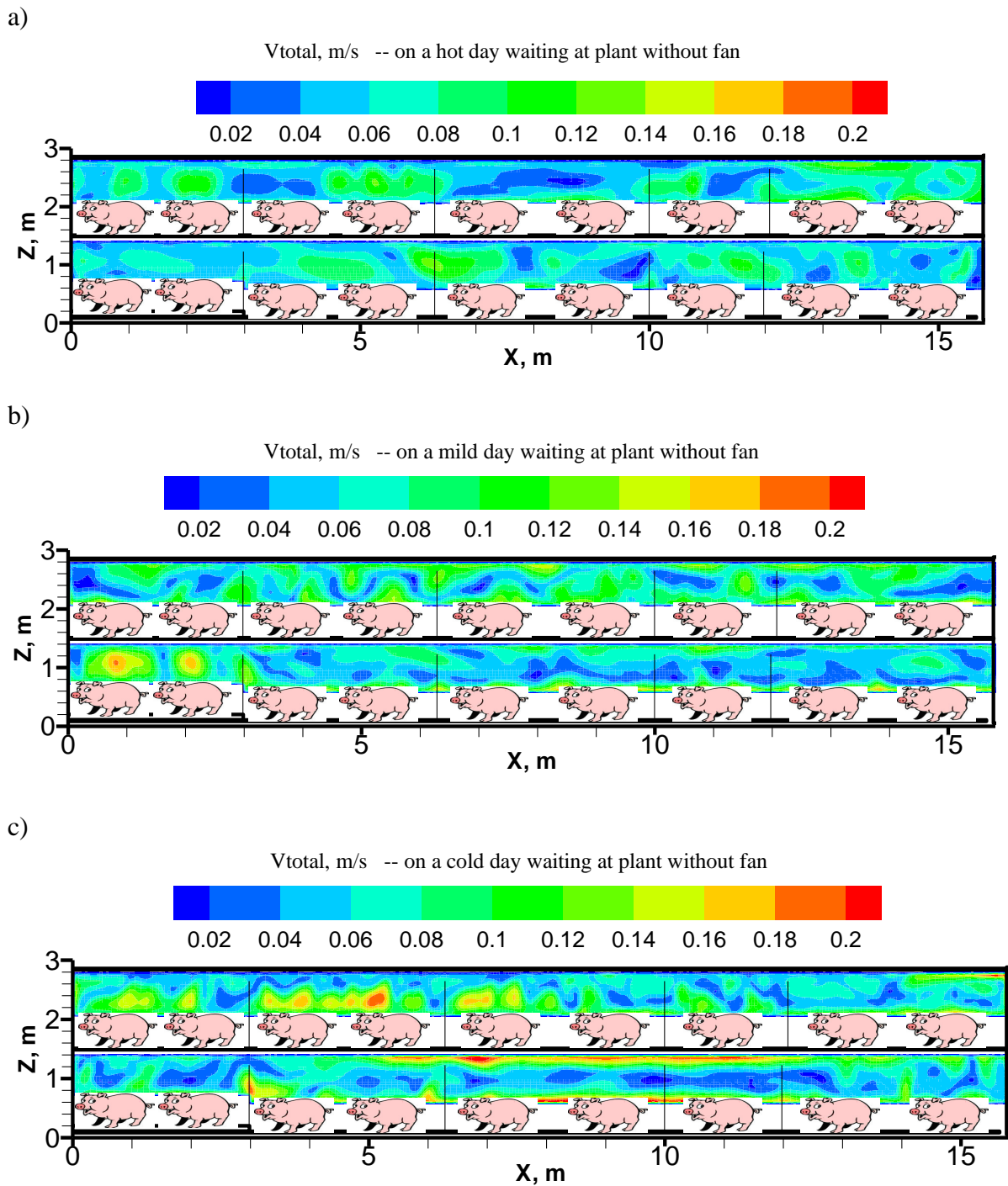
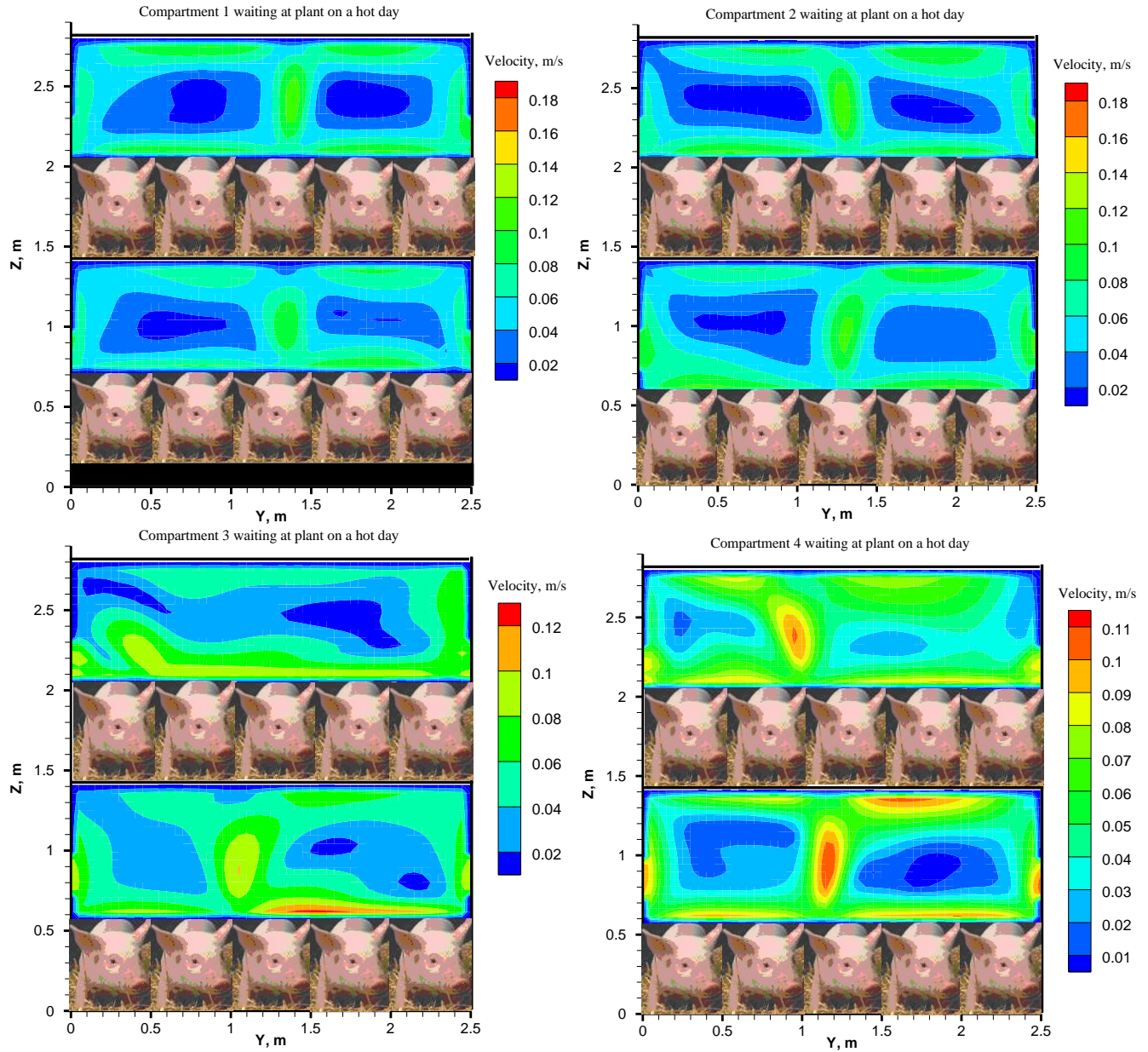


Figure C.40. Air velocity through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a hot day – without any external fans operating [Simulation 4].



Compartment 5 & 6 waiting at plant on a hot day

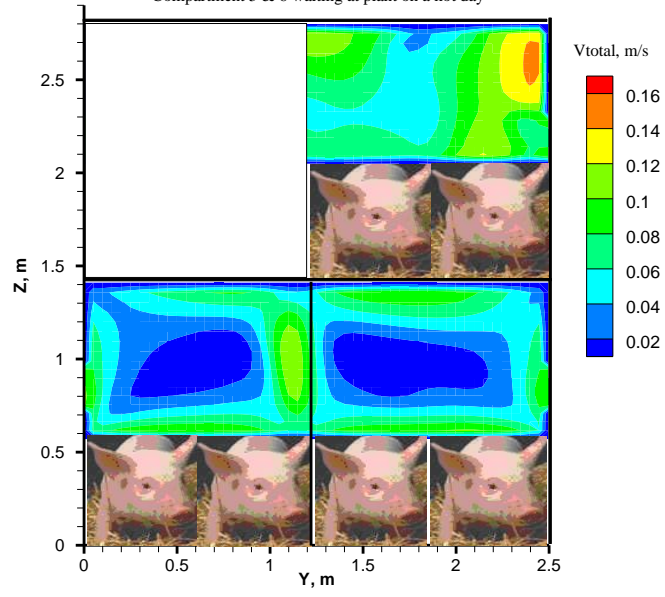
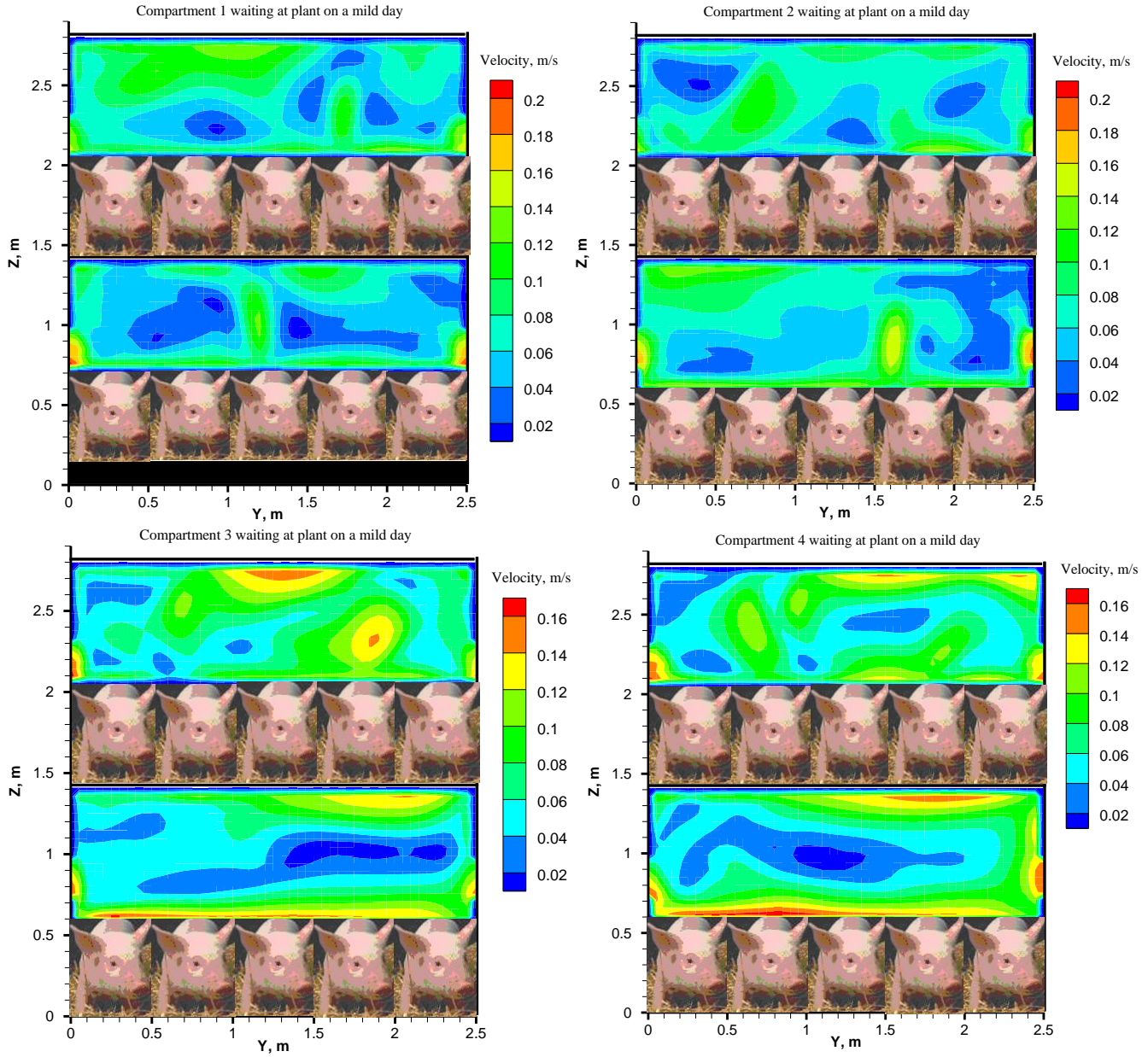


Figure C.41. Air velocity through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a mild day – without any external fans operating [Simulation 9].



Compartment 5 & 6 waiting at plant on a mild day

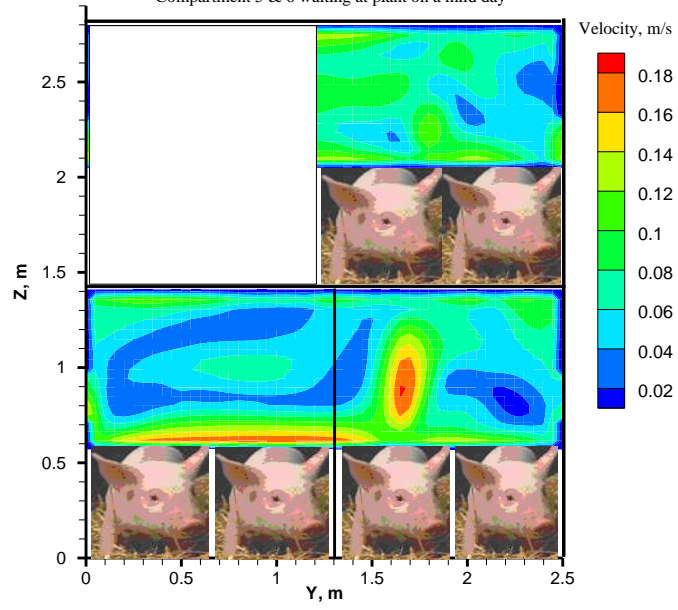
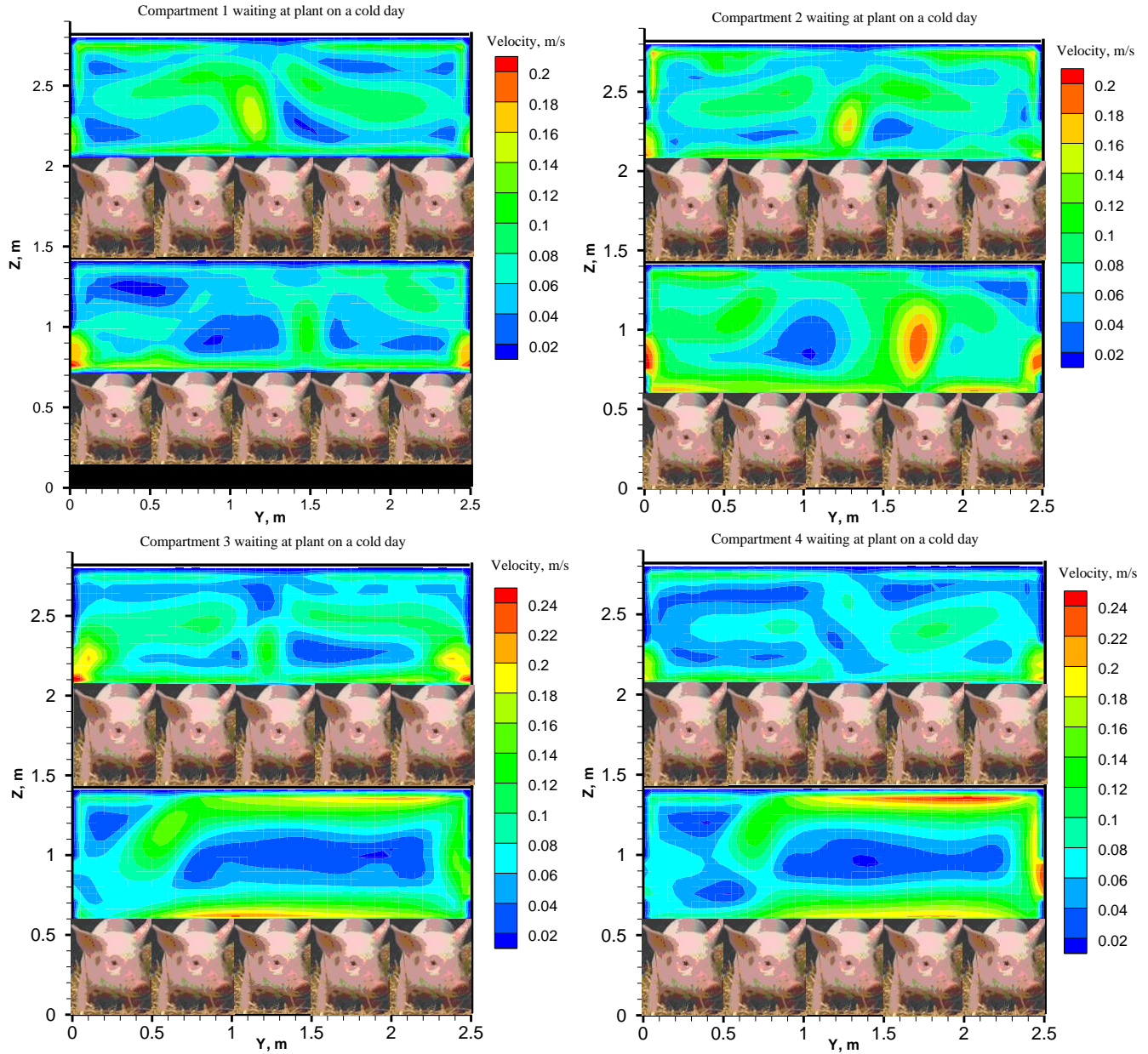


Figure C.42. Air velocity through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a cold day – without any external fans operating [Simulation 14].



Compartment 5 & 6 waiting at plant on a cold day

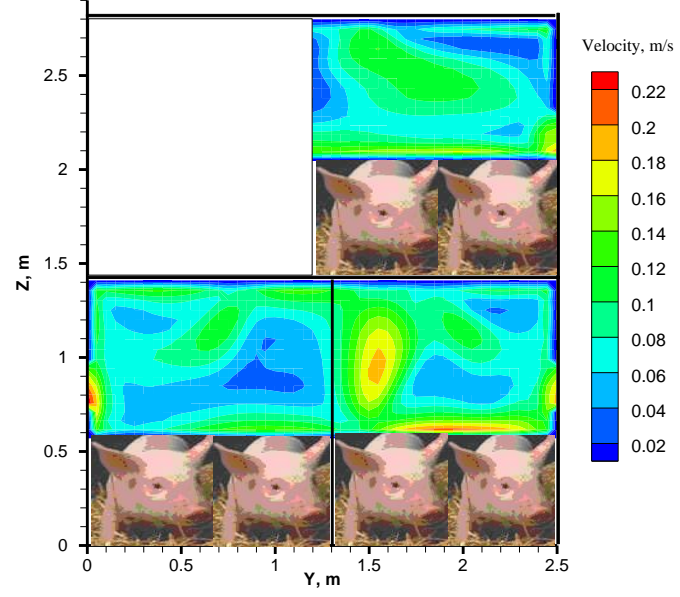


Figure C.43. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

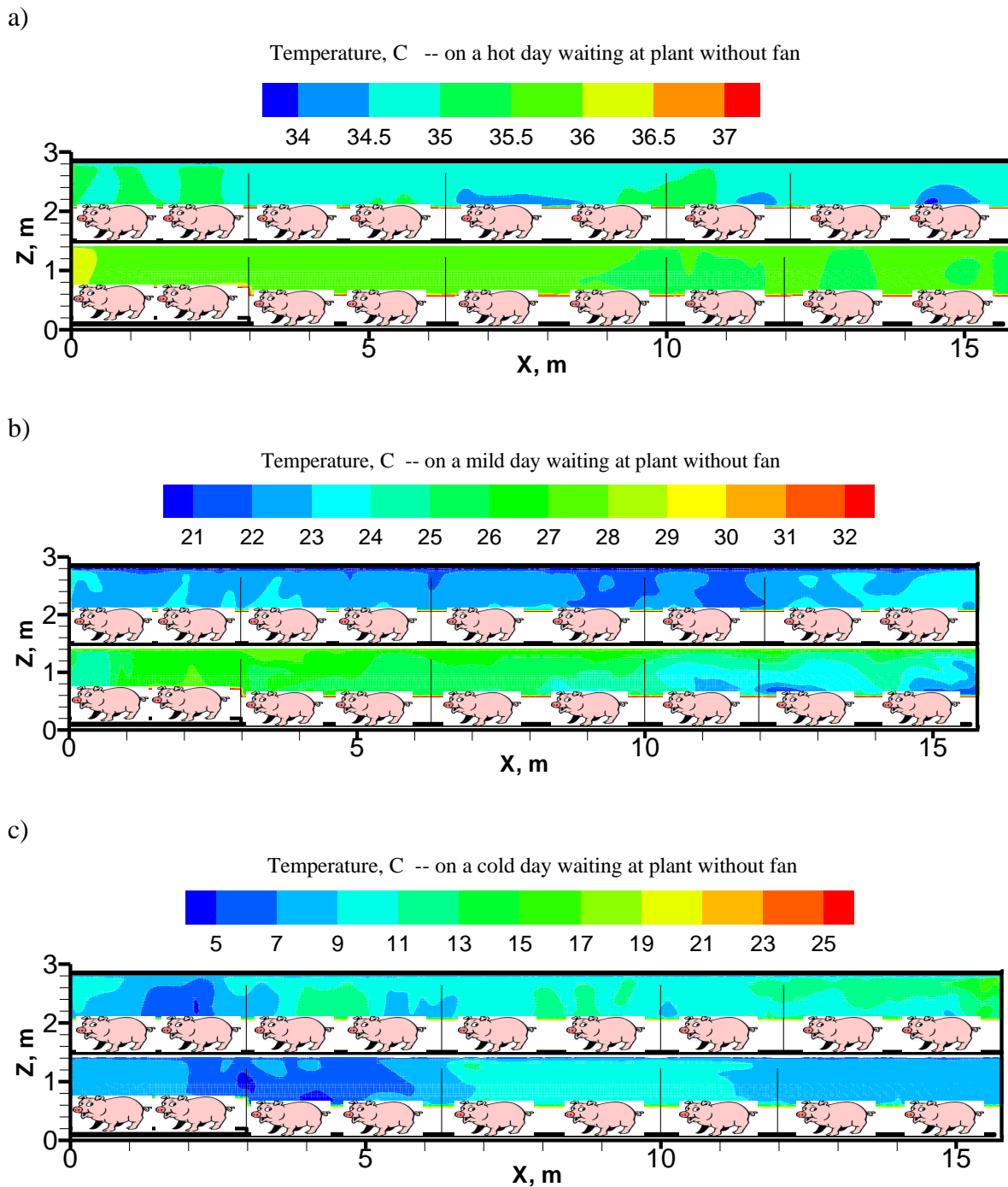
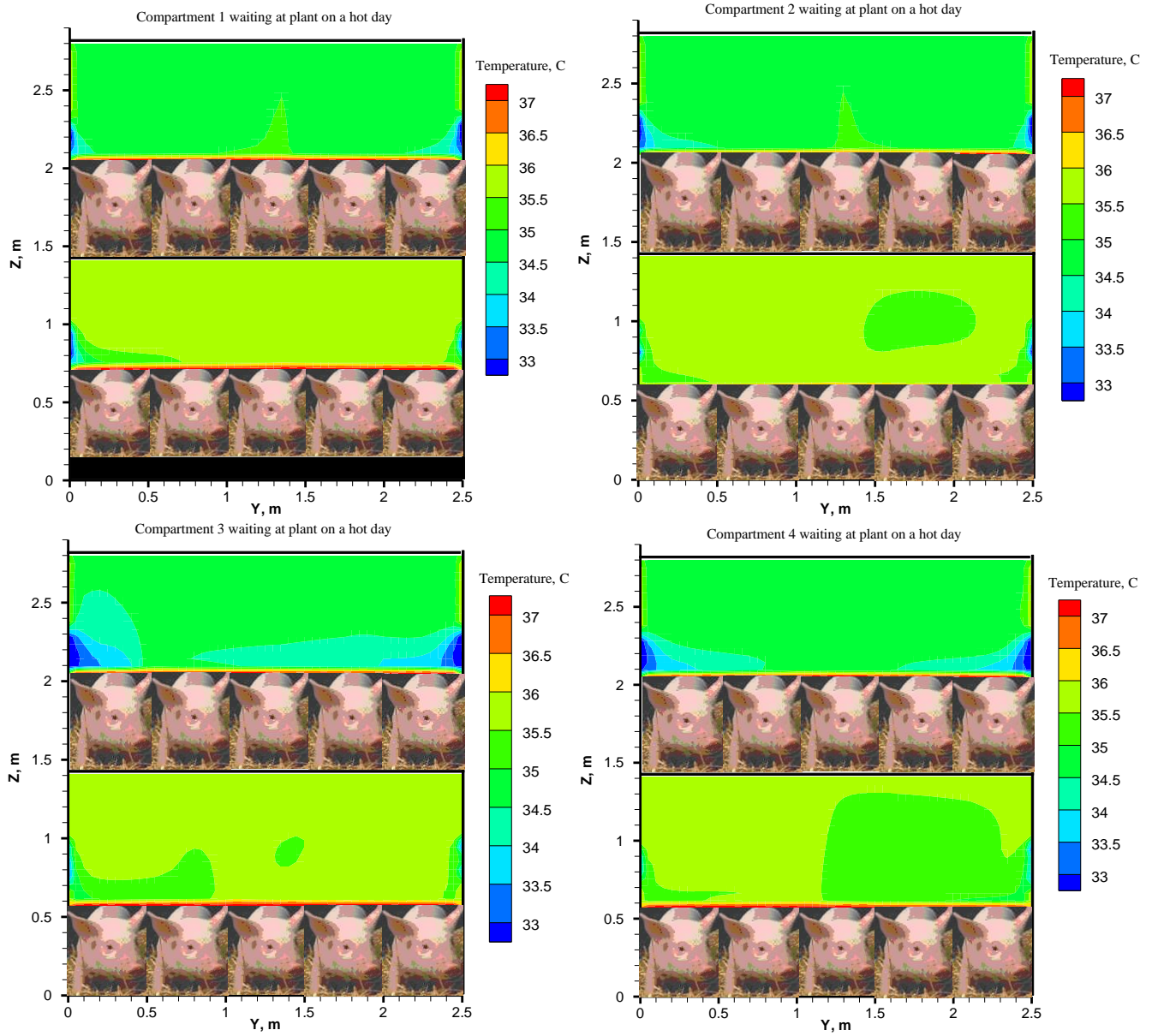


Figure C.44. Air temperature through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a hot day – without any external fans operating [Simulation 4].



Compartment 5 & 6 waiting at plant on a hot day

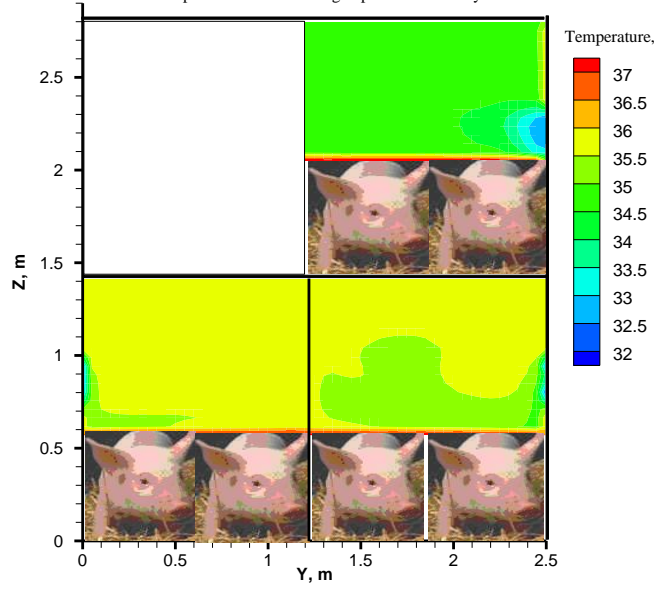
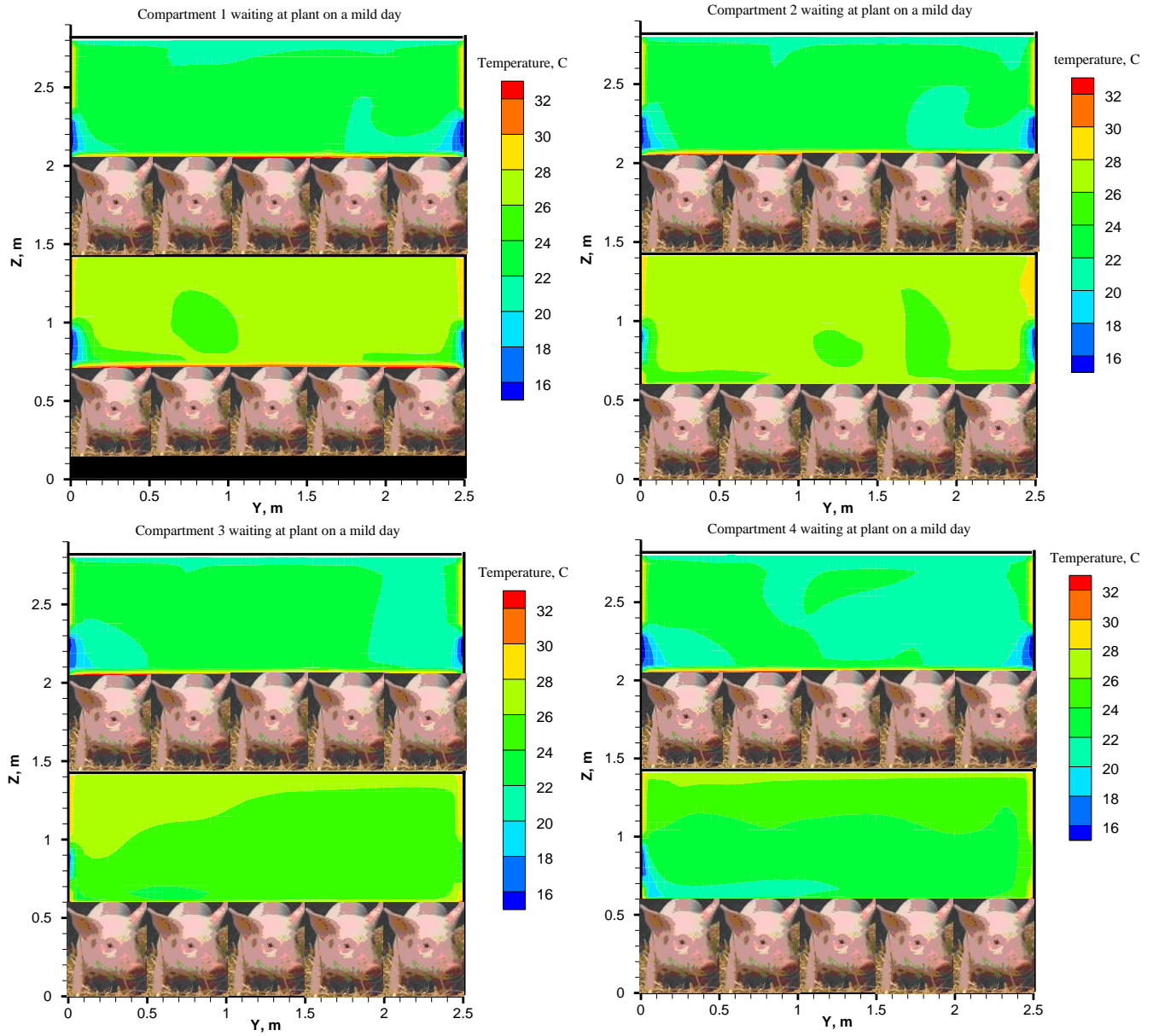


Figure C.45. Air temperature through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a mild day – without any external fans operating [Simulation 9].



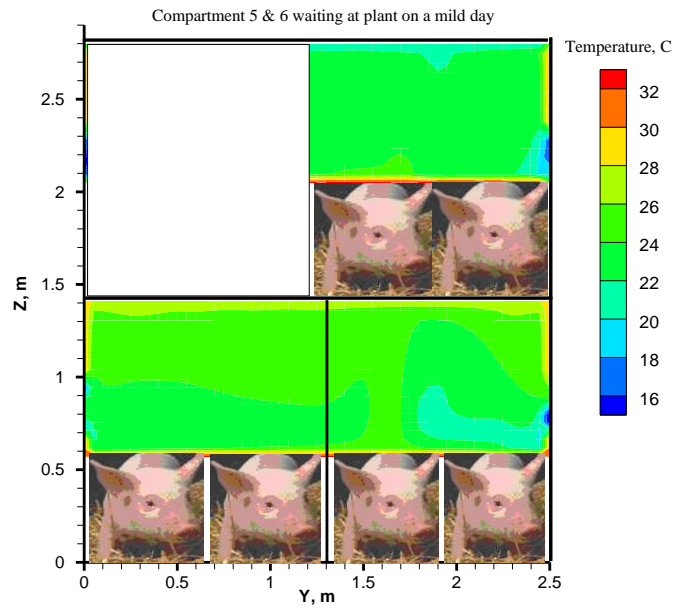
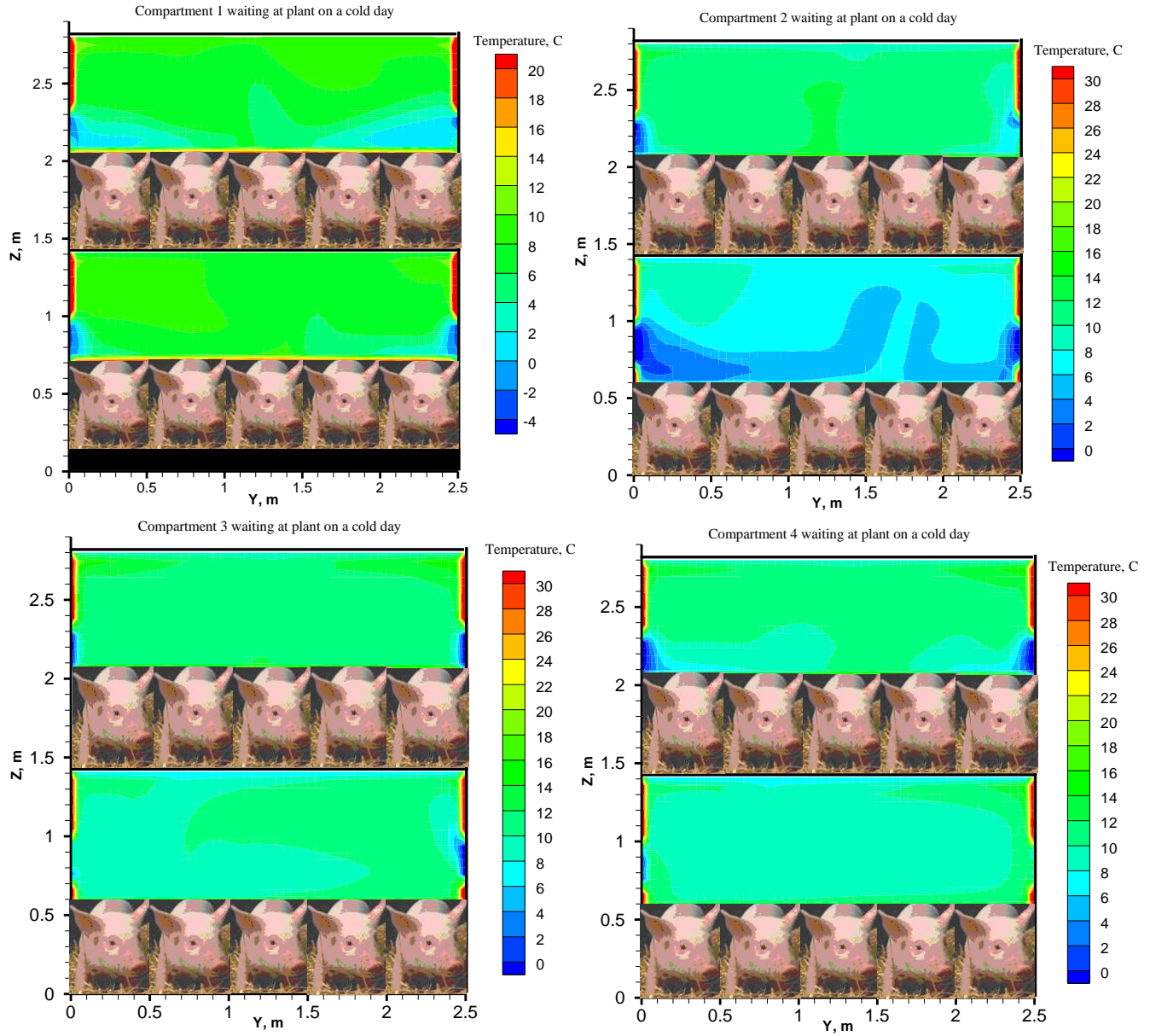


Figure C.46. Air temperature through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a cold day – without any external fans operating [Simulation 14].



Compartment 5 & 6 waiting at plant on a cold day

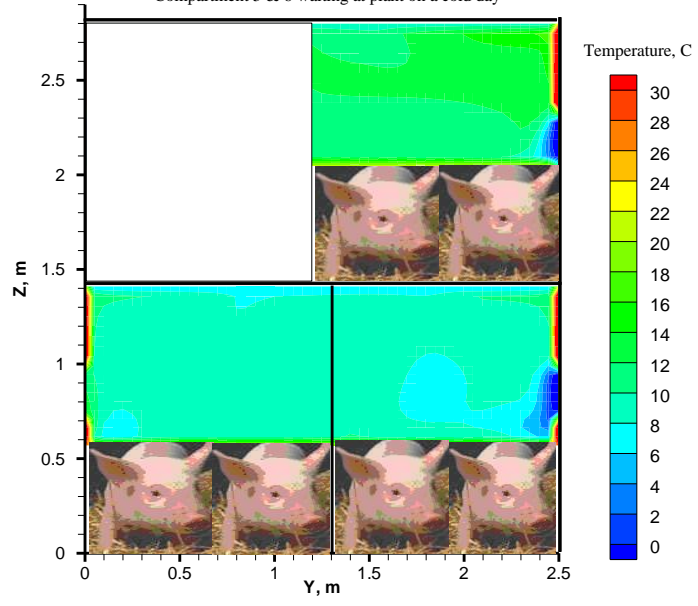


Figure C.47. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

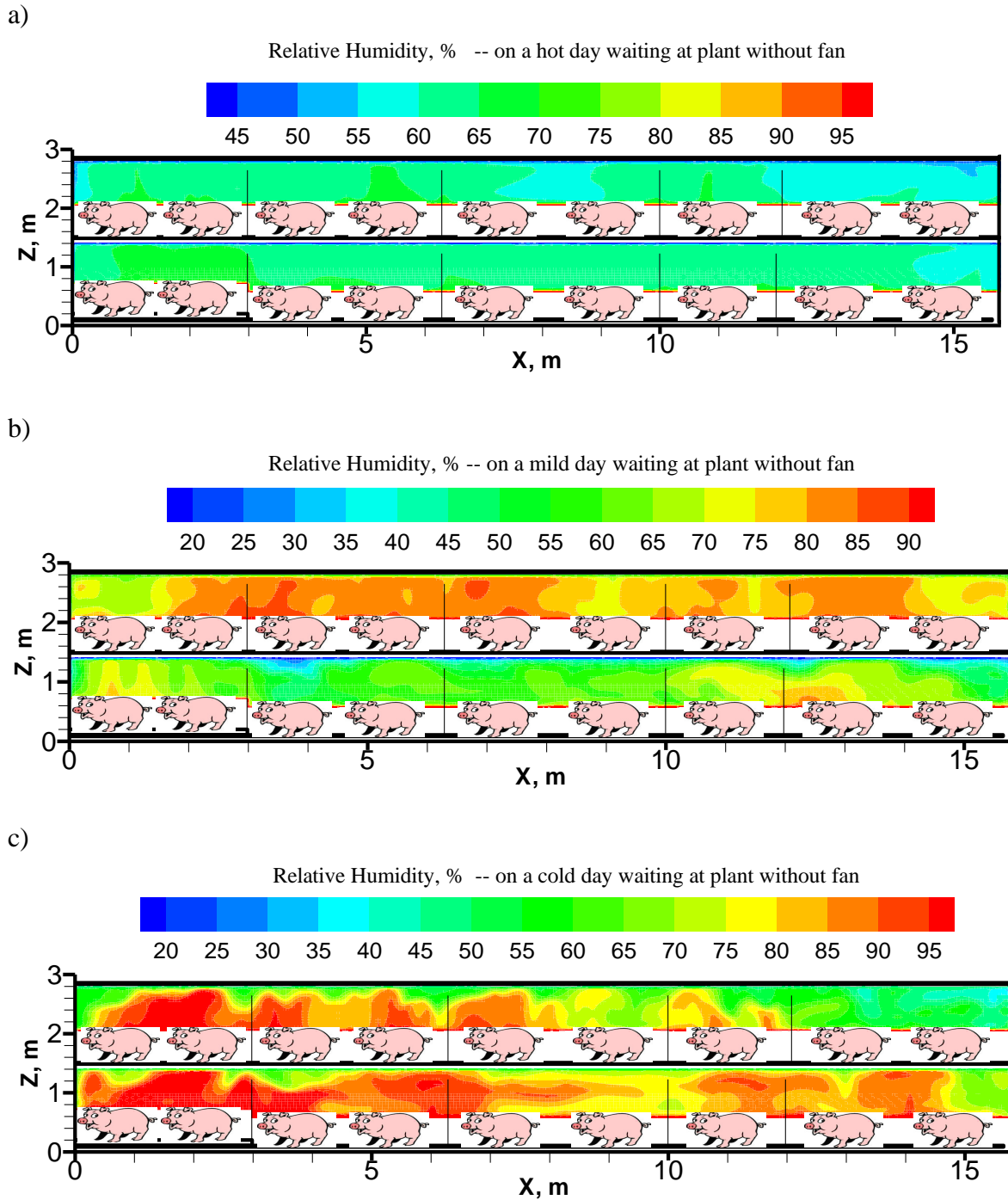


Figure C.48. Air relative humidity through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a hot day – without any external fans operating [Simulation 4].

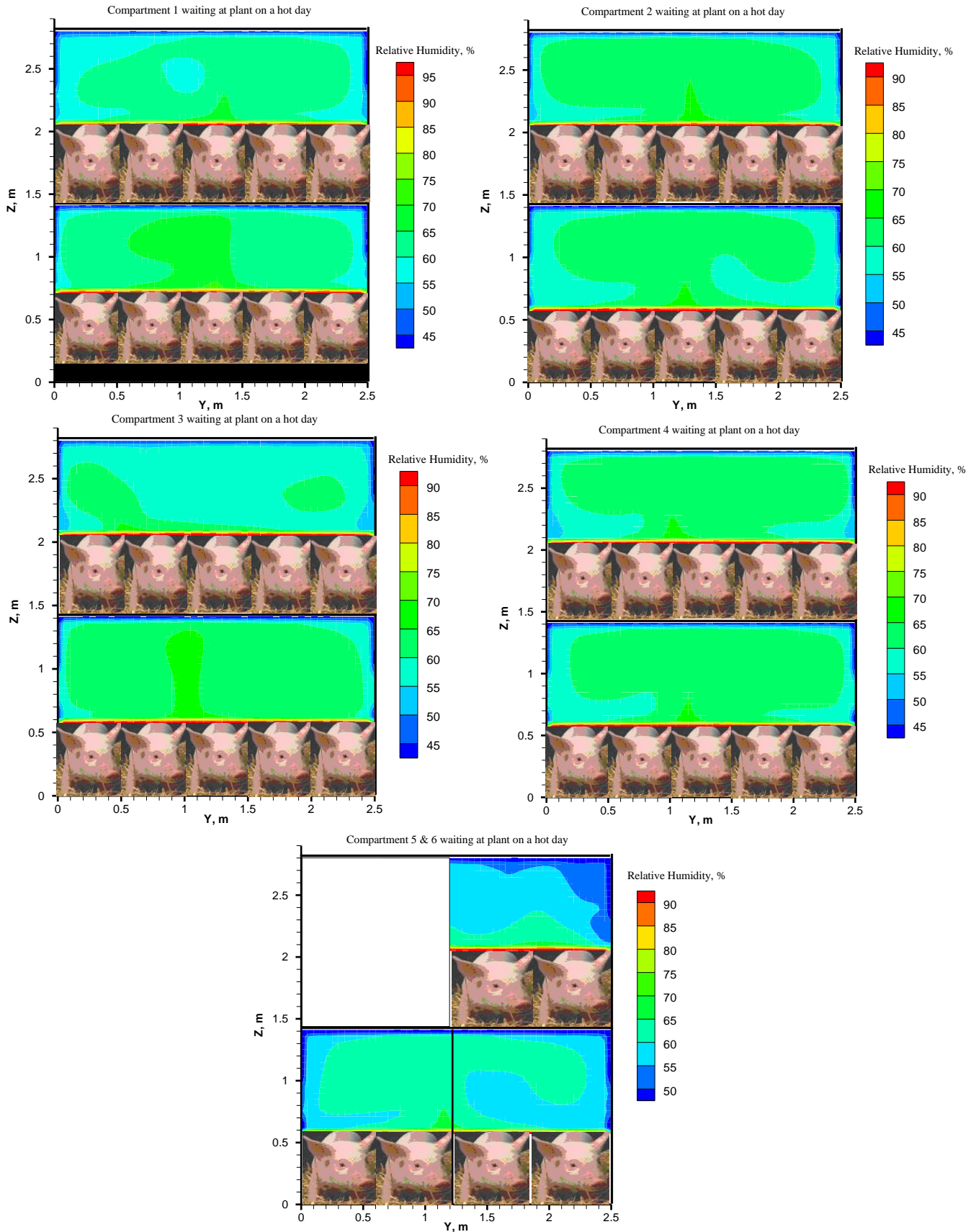


Figure C.49. Air relative humidity through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a mild day – without any external fans operating [Simulation 9].

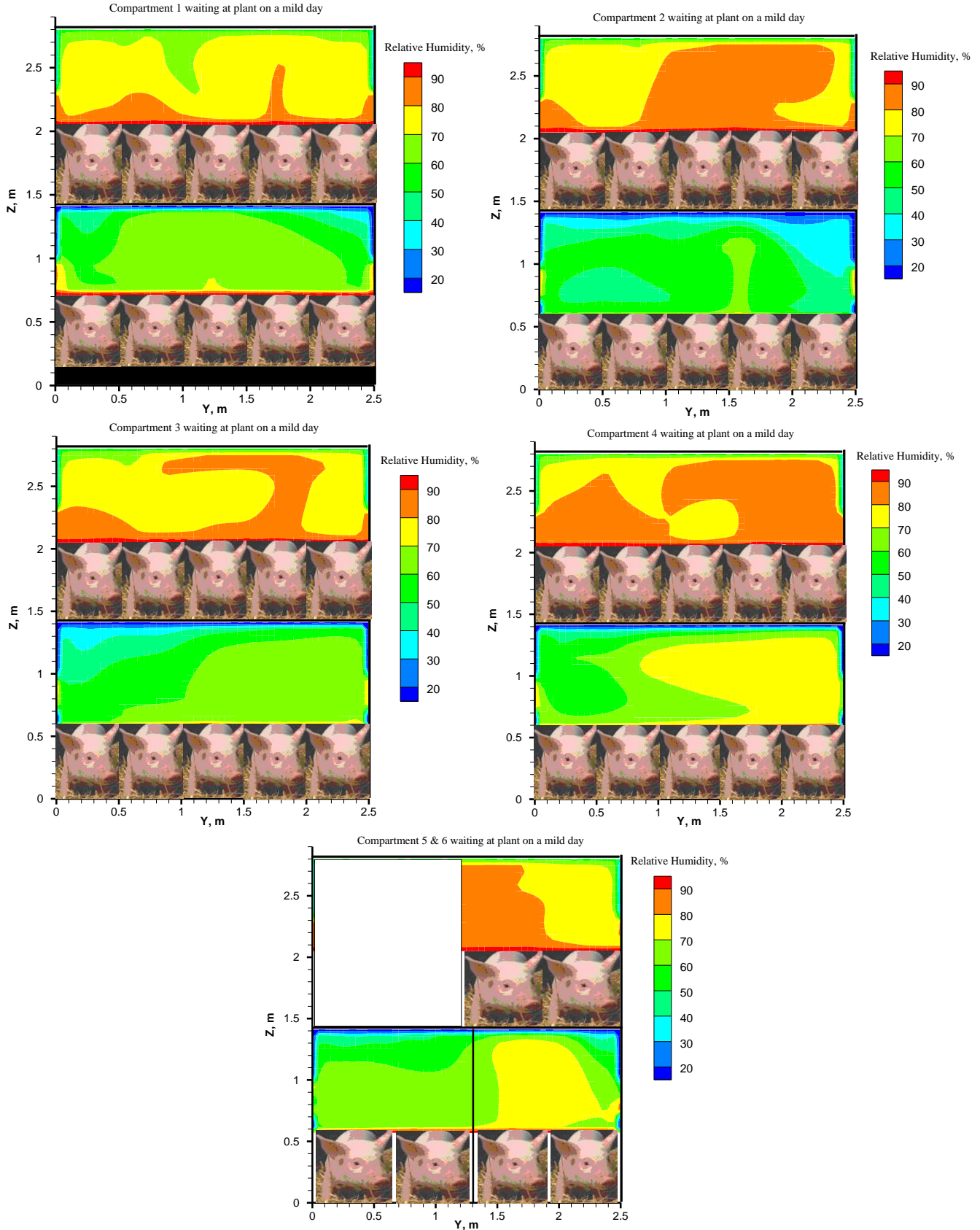


Figure C.50. Air relative humidity through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a cold day – without any external fans operating [Simulation 14].

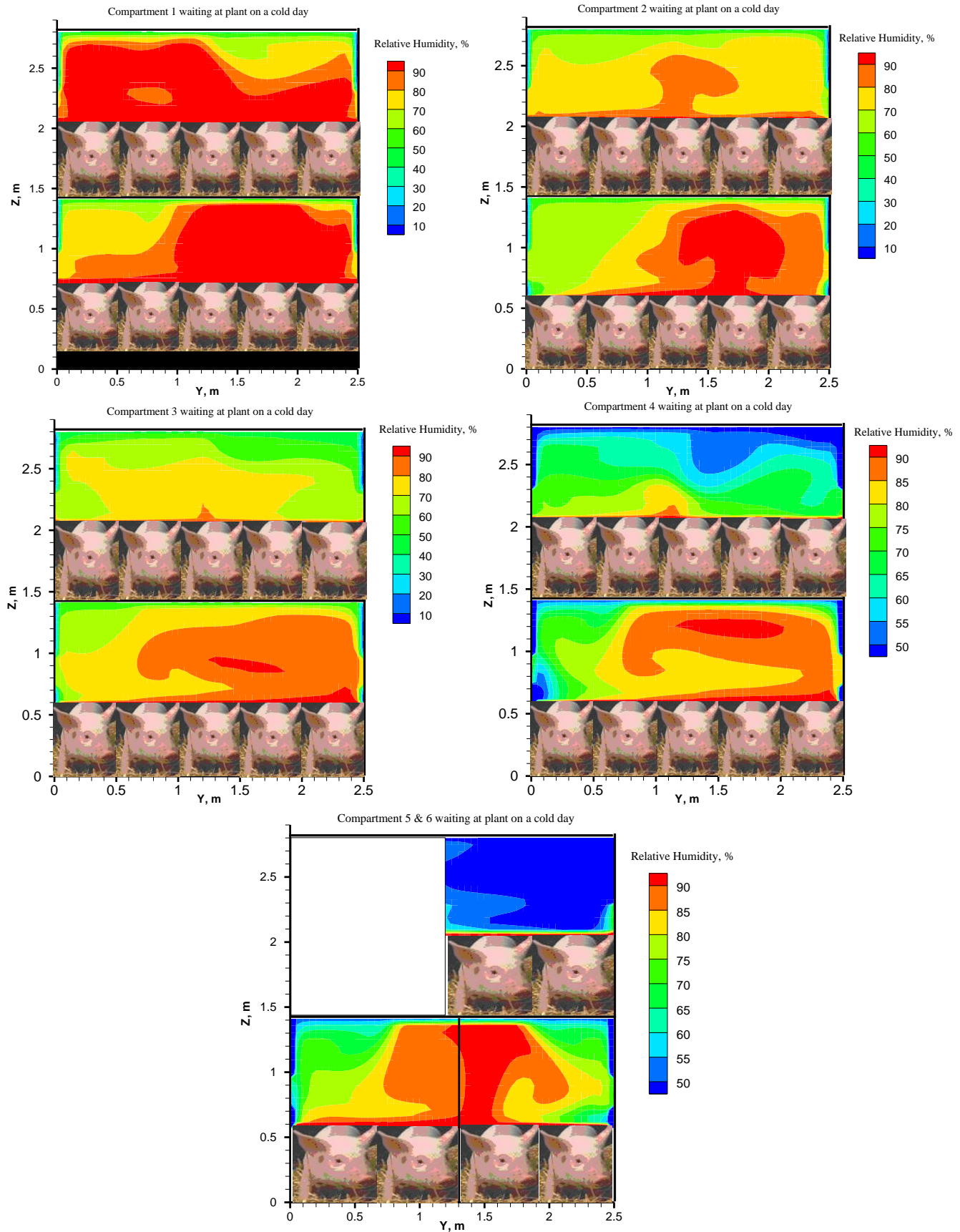


Figure C.51. Air carbon dioxide concentration through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – without any external fans operating [Simulations 4, 9, and 14, respectively].

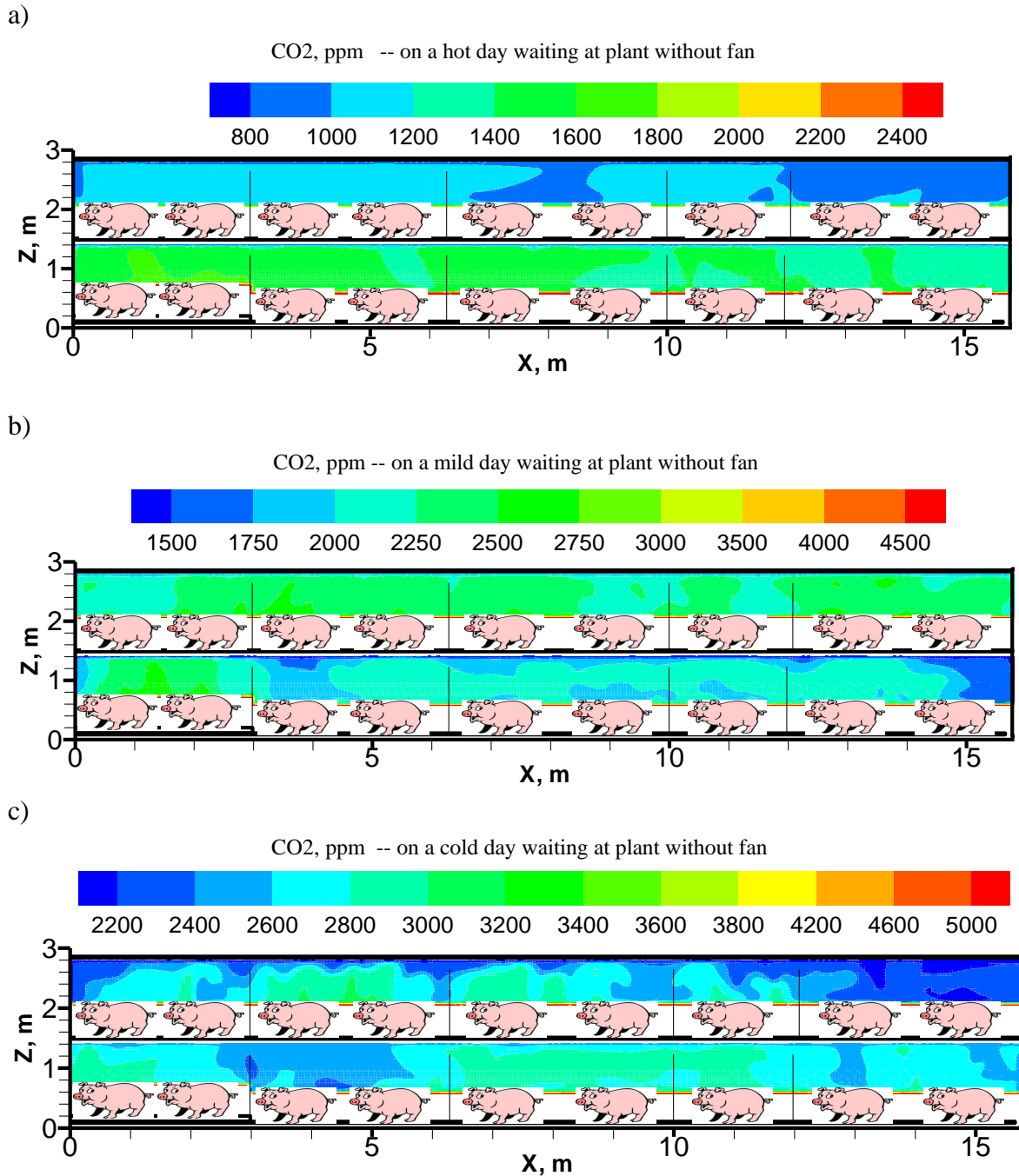
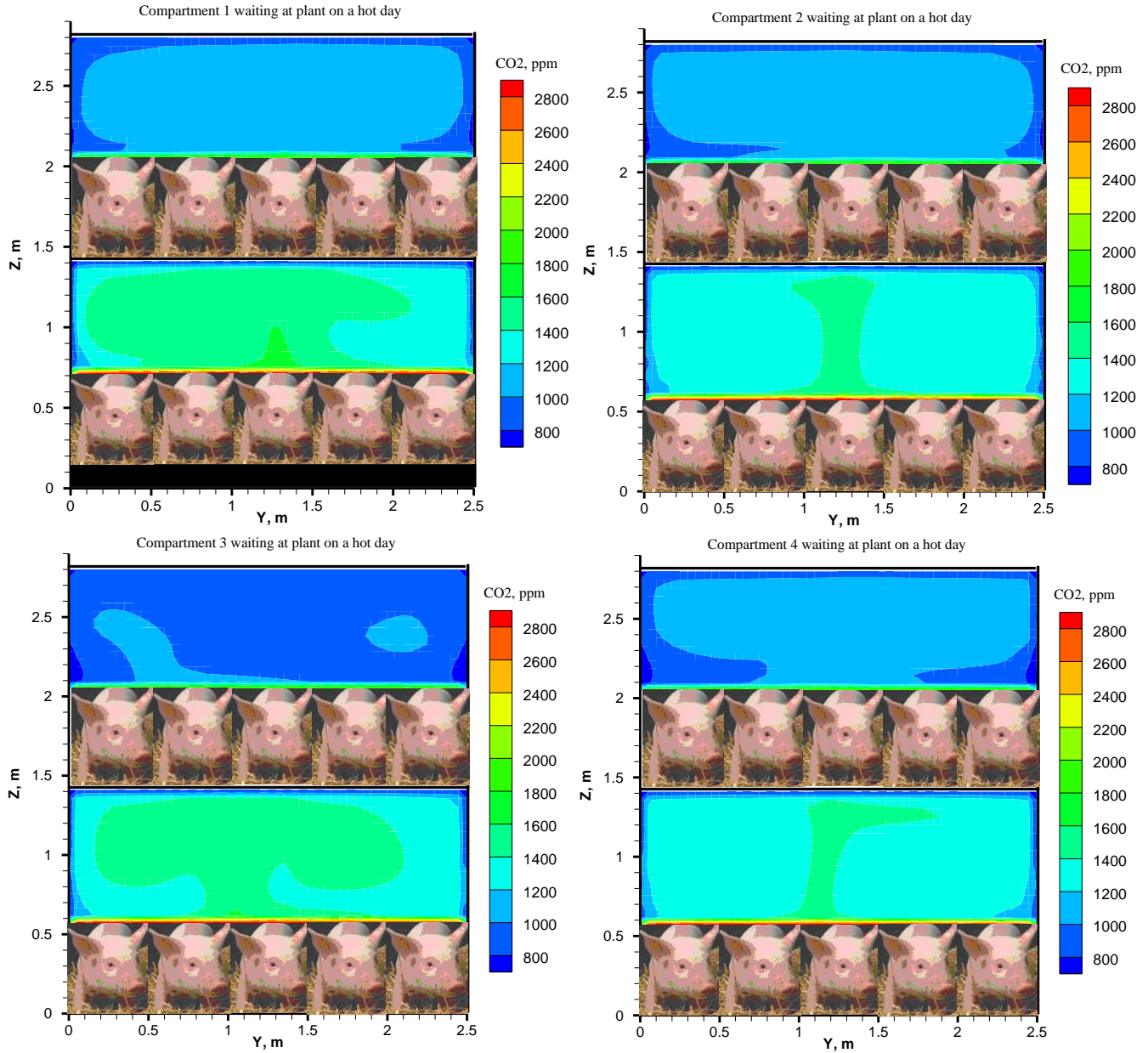


Figure C.52. Air carbon dioxide concentration through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a hot day – without any external fans operating [Simulation 4].



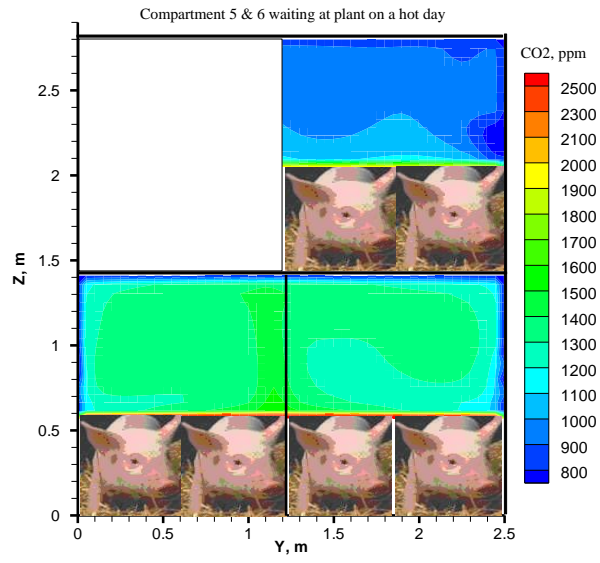
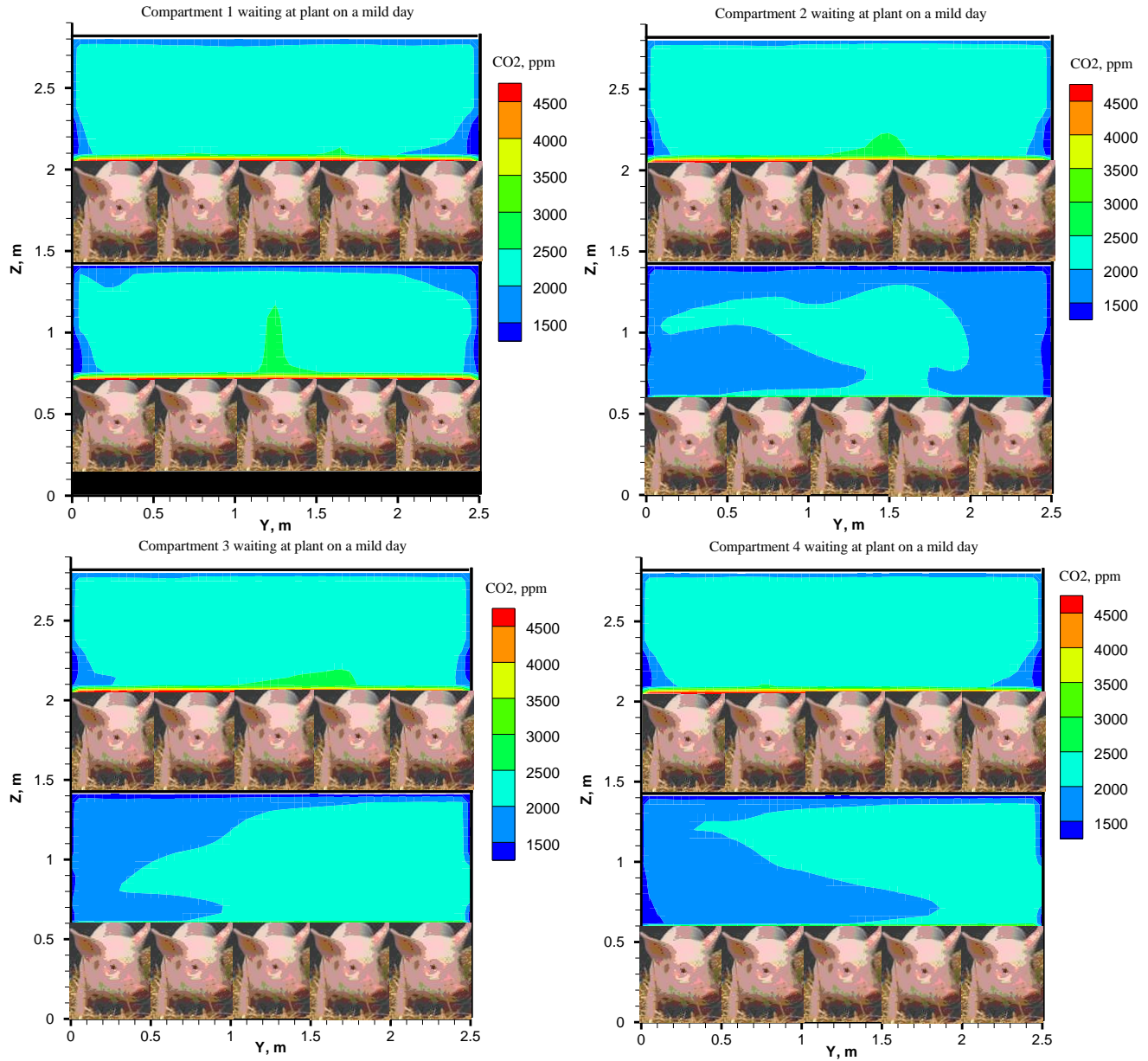


Figure C.53. Air carbon dioxide concentration through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a mild day – without any external fans operating [Simulation 9].



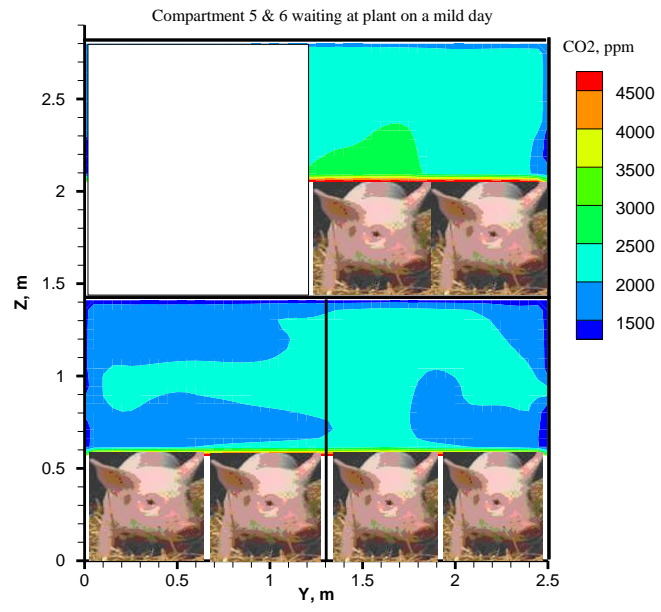
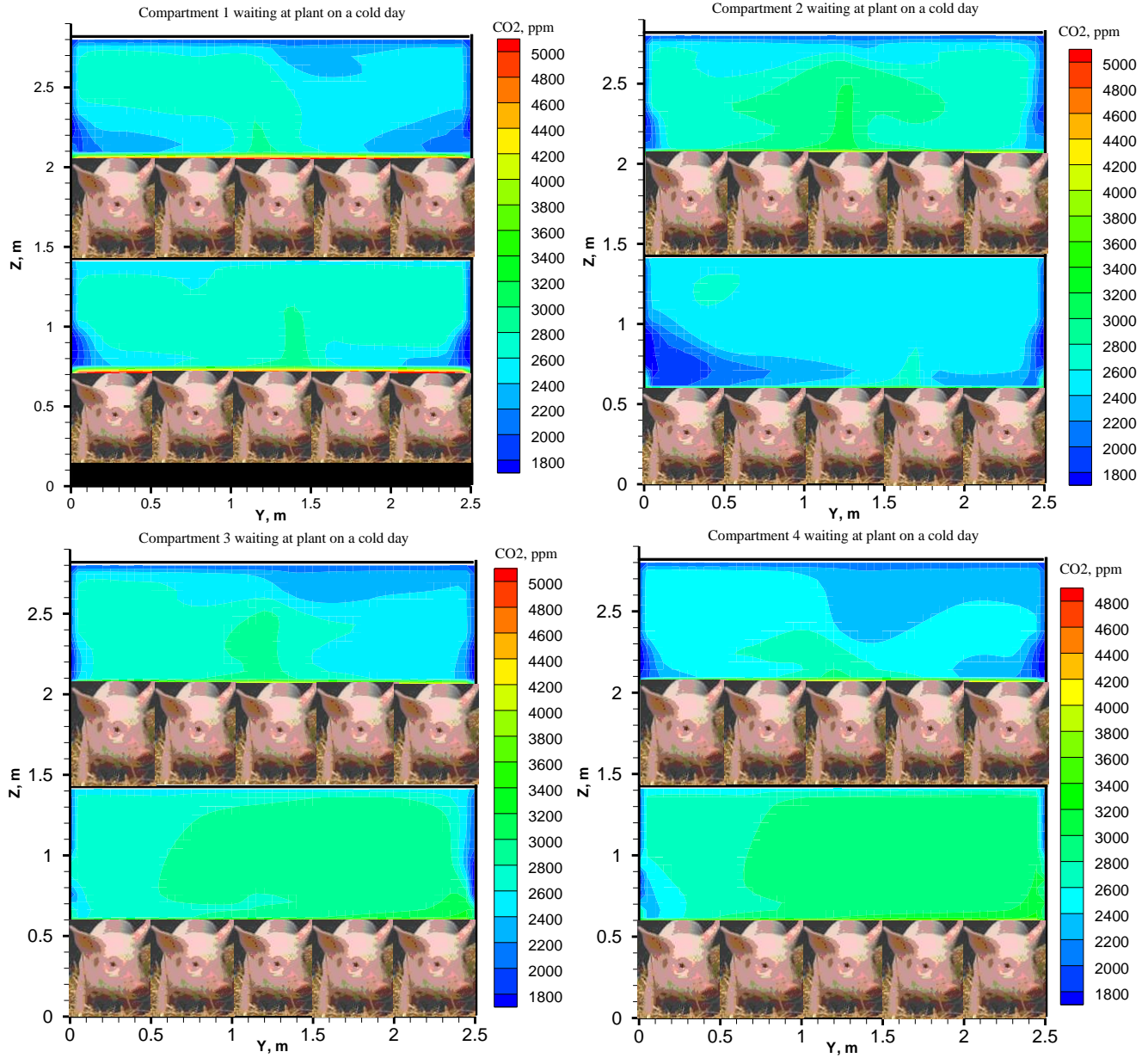


Figure C.54. Air carbon dioxide concentration through the transverse sections of the trailer during the period the trailer was standing, waiting at the plant on a cold day – without any external fans operating [Simulation 14].



Compartment 5 & 6 waiting at plant on a cold day

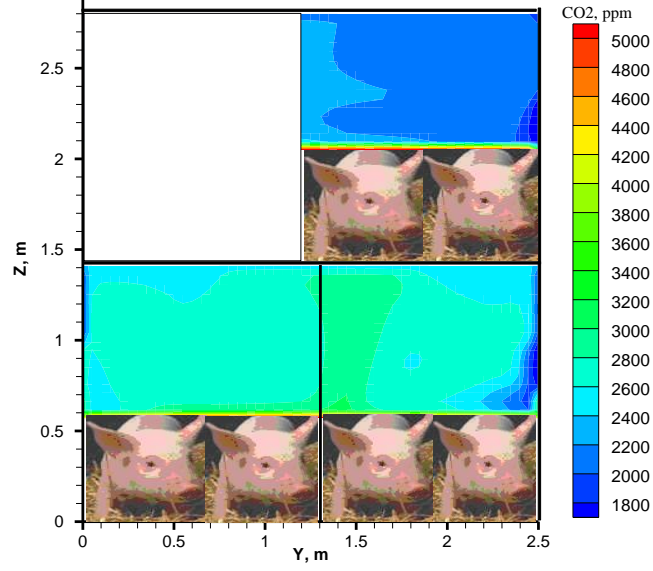


Figure C.55. Air velocity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 5, 10, and 15, respectively].

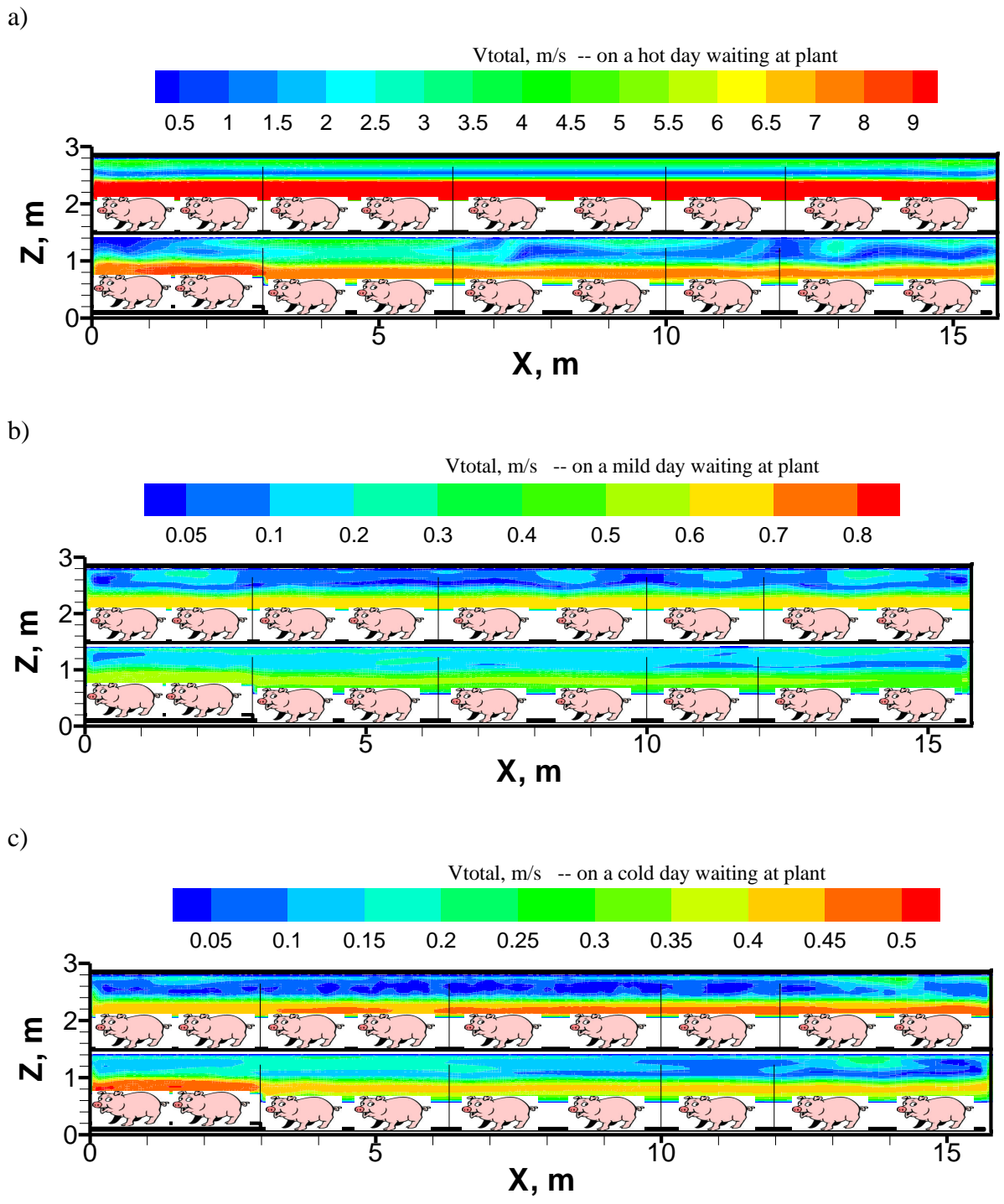


Figure C.56. Air temperature through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 5, 10, and 15, respectively].

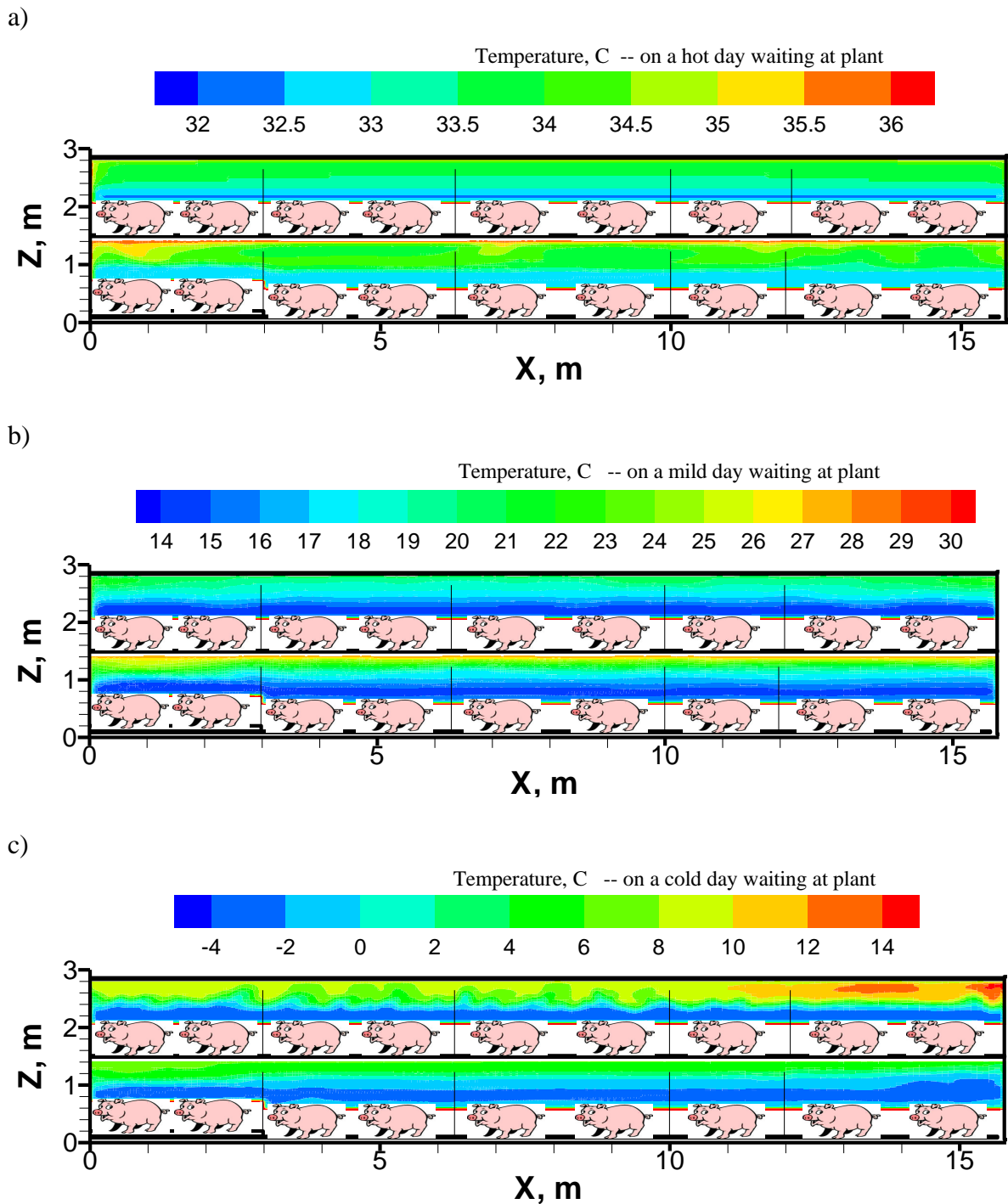


Figure C.57. Air relative humidity through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 5, 10, and 15, respectively].

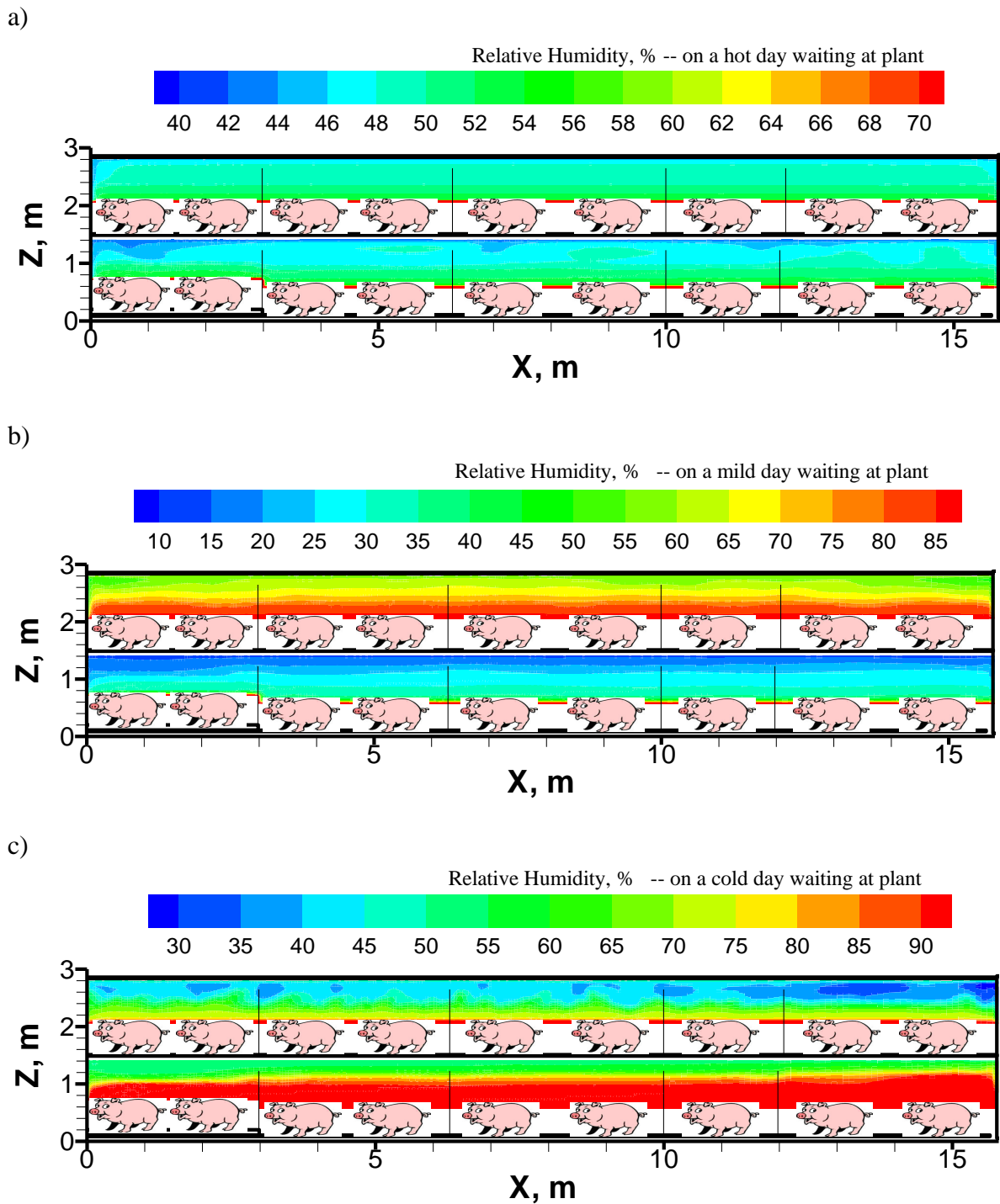
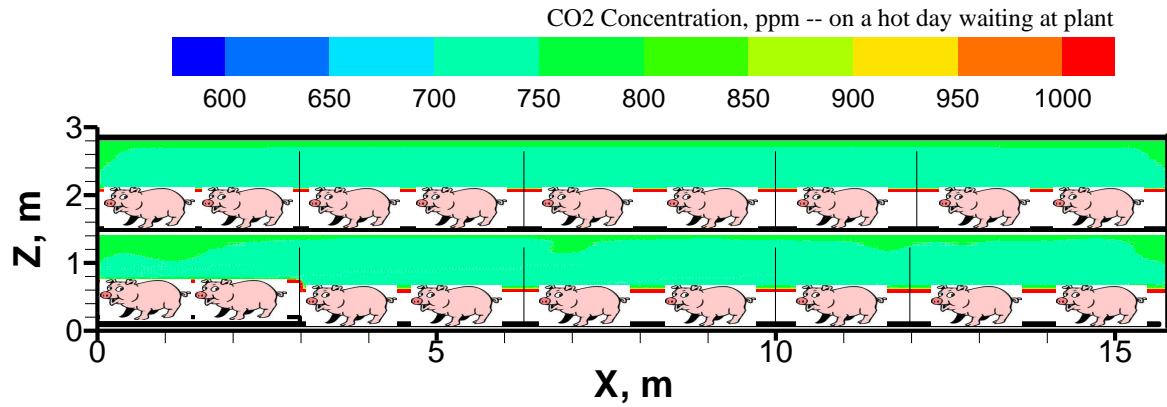
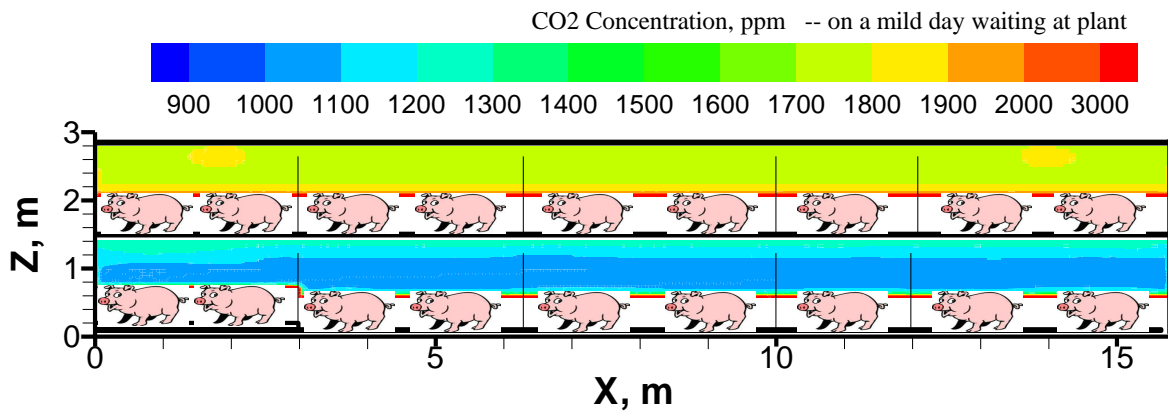


Figure C.58. Air carbon dioxide concentration through the longitudinal section in the center of the trailer during the period the trailer was standing, waiting at the plant on a) hot, b) mild, and c) cold days – with external fans operating [Simulations 5, 10, and 15, respectively].

a)



b)



c)

