University of Southern Queensland
Faculty of Engineering and Surveying

Computational Fluid Dynamics (CFD) Investigation for Improving Pigs' Housing Design

A dissertation submitted by

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ABSTRACT

Pigs are subjected to intensive environment control and management for higher productivity due to their sensitivity to climatic variation, which affects their growth. The aim of the current work is to numerically model the air speed and temperature in mechanical ventilation pig housing to achieve optimum environment control. The simulation model was assumed as a steady two-dimensional numerical model including the effect of buoyancy, turbulence and heat generated by the pigs. The model was solved using the computational fluid dynamics software, Fluent, which is based on the integral volume method. Air flow pattern and temperature inside the pig housing and at the pigs' level were predicted for different arrangements of inlet widths and inlet velocities in the range of 1 – 5 ms^{-1}. Different layouts were set up to determine the optimum design for the thermal comfort zones under daylight situation with ambient temperature of 30ºC and night situation with ambient temperature of 26ºC. From the analysis, location of inlets and outlets has to be carefully considered in order to enhance the air distribution in the pig housing. The use of water sprayer system during daylight was essential for pig housing in Malaysia to provide thermal comfort for the pigs. CFD analysis helped to identify problems in the design and offer suggestion for improvements. However, more work must be done to further evaluate other arrangements, and to conduct three dimensional simulations.

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Limitations of Use

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set put in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Date

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NOMENCLATURE

$C\mu$	constant used for turbulent viscosity
$C_1\varepsilon$	constant used in viscous dissipation of turbulence kinetic energy
$C_2\varepsilon$	constant used in viscous dissipation of turbulence kinetic energy
$C_3\varepsilon$	constant used in viscous dissipation of turbulence kinetic energy
C_p	specific heat (J/kgK)
G_b	turbulent production due to buoyancy
G_k	production term
g	gravitation constant (9.81m/s^2)
K	thermal conductivity (W/mK) or turbulence kinetic energy (m^2/s^2)
p	average pressure (Pa)
q	heat flux (W/m^2)
Y_m	compressible turbulence to the overall dissipation rate
k	turbulent kinetic energy
ε	rate of dissipation
u,v	average velocities in the x and y directions
T	average temperature
ρ	density (kg/m3)
υ	kinematics viscosity (m^2/s)
β	coefficient of thermal expansion (1/K)
α	thermal diffusion coefficient
μ	viscosity (kg/m/s)
$\sigma_k, \sigma_\varepsilon$	turbulent Prandtl numbers for k and ε, respectively
μ_t	turbulent viscosity
u^2 (bar)	normal stress
ωk	angular velocity
Ω_{ij} (bar)	mean rate-of-rotation tensor viewed in a rotating reference frame

GLOSSARY OF TERMS

CFD	Computational Fluid Dynamics
LCT	Lower Critical Temperature
UCT	Upper Critical Temperature
ECT	Evaporative Critical Temperature
2D	Two Dimensional

CHAPTER ONE

INTRODUCTION

Malaysia is a country self sufficient in the supply of pig meat. The swine industry underwent a significant restructuring in the aftermath of the Nipah virus epizootic in 1998/99 that resulted in the closure of approximately 950 farms. There are at present about 824 farms in operation serving about 1.5 million pigs. The export of live pigs to Singapore has ceased since 1999 but the expansion of the remaining farms has enabled the country to sustain its self sufficiency. Due to environmental problems such as smell and air pollution, there is a need for the swine industry to adapt ventilation system in pig housing. The industry is also trying to persuade the government to support the development of pig farming areas (PFAs) and the development of environment friendly farms as PFAs.

1.1 Ventilated Pig Housing

Profitable and hygienic pig production depends on the provision of suitable housing. Pigs need warmth, dry bed and protection from extreme weather conditions. They have certain minimum requirements for space, fresh air, hygienic conditions and access to feed and water. The accommodation provided should not lead to illness or injury.

A good pig housing design will increase production efficiency by maintaining pigs at their thermal comfort zone across all seasons. For all classes of pigs there is a range of air temperatures within which productivity is optimum. This range of temperatures, called the thermal neutral zone, is usually very small for young piglets and feeder pigs (Moore, 1993.). During physical activity by the pigs, heat is released. Within its thermal zone, the pig is able to manage the release of their body heat to keep their temperature constant. The upper and lower limits of their comfort zones are called the lower critical temperature (LCT) and the evaporative critical temperature (ECT).

- Lower Critical Temperature (LCT)

  At the lower (cool) end of its thermal comfort zone, the pig is able to regulate body temperature by constricting blood vessels in or near the body surface to minimize heat loss, lying with minimum skin surface exposed to cool floors, and erecting the hair coat. When these mechanisms are insufficient to maintain the pig's body temperature; more energy is needed to produce heat. The point at which extra food energy begin to be diverted to keep the animal warm is called the lower critical temperature (LCT), and the efficiency of converting food to weight gain is reduced.

- Evaporative Critical Temperature (ECT)

  At this thermal comfort zone, the pig will try to avoid itself of unneeded heat released by digestion and physical activity, e.g. dilating blood vessels near the body surface to maximize heat loss, standing under a sprinkler, and lying stretched out on cool floors. When these mechanisms are insufficient, the pig reduces food intake and this point is called evaporative critical temperature (ECT).

- The Upper Critical Temperature (UCT)

  The highest tolerable temperature beyond which serious problems are likely to occur and this is generally 6 to 8°C above ECT.

The thermal comfort zone is close to body temperature of newborn pigs and it generally declines with age. Table 1.1.1 presents the combination of acceptable range of temperature, velocity, flow rate and relative humidity level as a function of the size of the pigs in Malaysia.

Table 1.1.1: Combination range of preferable temperature, velocity, flow rate and relative humidity level for different sizes of pig

Type and weight	Preferred temperature °C	Velocity range, v(ms^{-1})	Ventilation Rate, L/s per pig	Relative Humidity level, (%)
Dry sow	13-18	>5	96	60
Weanling pig (7-25 kg)	21-27	> 0.25	0.016	30
Grower (25-69 kg)	23	0.5-3	0.042	40-60
Finisher (60-100 kg)	29	1-4	0.048	50
Combined (40 to 70 kg)	25	0.5-8	0.045	50-70

(Sources: Livestock farmer's Association of Malaysia, Selangor, Sepang)

Growers and Finishers pig type will be used in this study. If pigs are healthy, not exposed to drafts at floor level, kept in groups of eight or more per pen, and are provided with all the feed requried, the productivity of grow-finish pigs is usually unaffected by air temperatures between LCT and ECT. A change in any of these conditions will narrow the pig's acceptable combination of preferable range of temperature, velocity, flow rate and relative humidity level.

Pigs in compartments are mainly stressed by climatic factors and non-climate factors. The main climatic factors are air temperature, humidity, air speed, gas, dust, and typical non-climatic factor is stocking density. Most of the climatic factors strongly depend on ventilation. Therefore, optimization of the ventilation system to match all the specific requirement of pigs is a key element in successful operation of any swine production facility. A well-designed and manageable ventilation system ensures the production of healthy pigs.

Ventilation removes low-quality air and replaces it with fresh air and high-quality air. There are two possible systems that can provide the required ventilation air, i.e. mechanical or natural system.

(a) Mechanical ventilation system uses fans to provide the required air flow rate. These systems are common in swine-grower and finisher units. The advantages of the mechanical system include better control of the air flow rate to match the needs of the livestock in the building, reduce number of drafts and more efficient use of distribution air in the building.

(b) Natural ventilation system uses no fans. It relies only on wind and heat thermal buoyancy to produce air movement. The main advantage of natural ventilation system is its low initial cost (no fans is needed) and no operating cost (its ability to move air without requiring any electricity). The disadvantage of the natural system is that one has very little control on the environment and a very careful design is required. For example, location of the inlets openings needs to be placed accurately to control the range of ventilation rates, which is influenced by air temperature, wind, insulation level, animal numbers and their activity level in the building. Because wind is one of the driving forces, the building orientation influences the design inlets, outlets and controls and this orientation must reflect the needs of the building in a natural ventilation system. Therefore, this type of ventilation system is more often used in housing of older pigs, i.e. hogs and gestating sow.

1.2 Objectives and Scope

The main objective of this project is to evaluate a particular design of pig housing in regard to its suitability for meeting the thermal comfort of the pigs housed and to recommend any changes in the design necessary to optimize its suitability. In order to achieve this, Computational Fluid Dynamics (CFD) is used to numerically determine the temperature, air speed and humidity concentration in mechanical ventilation system design for pig housing at different weather conditions. Ventilation is important for temperature and relative humidity control and for removal of gases, dust and odors. The size, position and number of air inlets bring in fresh air to supply animals needs and also location of exhaust fan are important parts of the ventilation system and are responsible for providing good air distribution and movement throughout the structure. Figure 1.2.1

shows a section with an adjustable long-slot inlet. The area of the opening make the incoming air accelerates to a speed that will throw a jet of fresh air across the ceiling. If the slot is too wide or the airflow is too low, this will form slow and lazy air stream causing draft. *(Draft means cool air moving over animals. Due to its heavier density, cool air drops when entering a warm space. Warm air moving over animals usually does not constitute a draft.).* The heavy cold air sinks unmixed to the floor, the lighter, warm room air is displaced upwards and the two layers remain separated, a very unhealthy situation for sensitive animals penned at floor level.

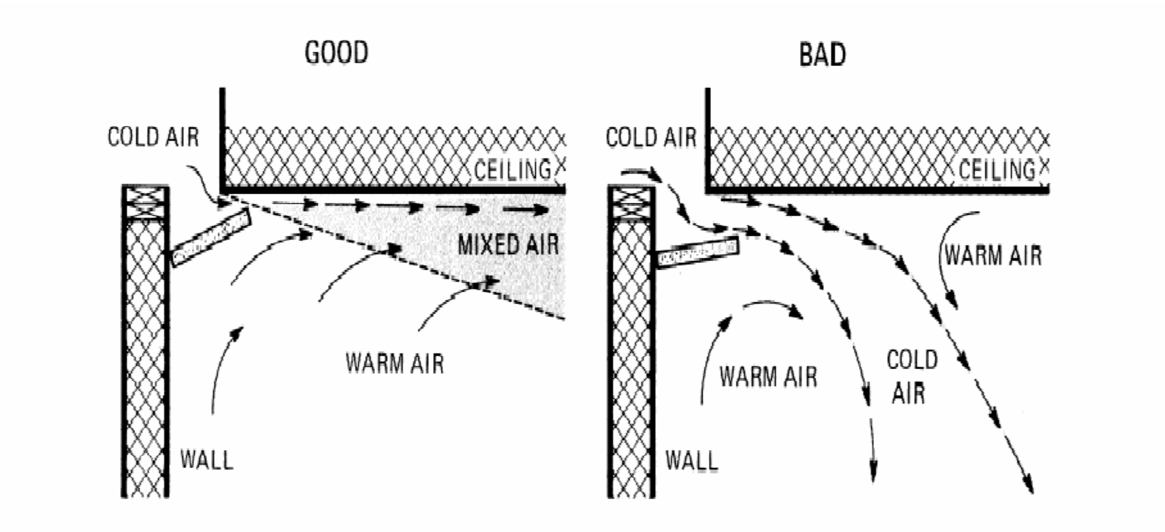


Figure 1.2.1 A section through an adjustable long-slot inlet.
(Sources: Canada plan service, m-plan 9710)

Good inlet design require thoughtful sizing, placement, and control, therefore inlets are critical to the success of the ventilation system and are the key to uniform distribution and complete mixing, giving acceptably uniform air quality throughout the livestock. Thus, different sized opening inlets at different positions are investigated. The objectives in this study are explained below:

- Research the background information relating to pig housing ventilation such as types, thermal comfort level of pigs at different ages, heat transfer.
- Research the information about the different inlets design and investigate the effect of air flow pattern caused by the design.

- Conduct a literature search for the topic.
- Model the mechanical ventilated pig housing in two-dimensional model, using CFD software "FLUENT 5.3" and investigate how the system components (e.g. fans, openings, control) affect the air flow pattern in pig housing.
- Vary the ambient temperature, air speed, inlet design, and outlets and examined the different arrangements to investigate which design meets the pigs' thermal comfort requirements.
- Present results, conclusion and recommendation for how to improve the pig housing design.

1.3 Dissertation overview

This dissertation is divided into 7 chapters. Chapter 1 introduced the research topic and explained on the objectives and scope of the research. Chapter 2 will provide a brief discussion on the background information, for example the characteristic of pig housing, temperature comfort zones for all classes of pigs, and the ventilation system and chapter 3 will summarize the details on the literature review before carry out the CFD simulations.

Next in Chapter 4, six arrangements of pig housing used in this investigation to study the effect of air flow pattern will be discussed. Chapter 5 will explain the mathematical model for the dimensional analysis and the numerical method which focuses on the explanation of the GAMBIT and FLUENT software, and the standard k-ε and realizable turbulence models used in the CFD simulations.

Chapter 6 presents the results and discussion from the simulation model. Finally, the results obtained as well as knowledge learnt from the project is summarized in Chapter 7.

CHAPTER TWO

BACKGROUND INFORMATION

Pig is of very ancient origin and existed from early times in many different parts of the world. Through the centuries, pigs were valued for their ability to eat household scraps therefore pigs are farmed mainly for their meat, and the most common cuts with which we are familiar are pork chops, pork fillet and shoulder of pork. Pork is a very versatile meat and is often used in Chinese cooking. In order to produce fresh meat, environmental consideration in pork production operation must include the welfare of the pigs and the protection of air and water quality.

2.1 Basic requirements for intensive pig housing

- **Environment (Temperature)**

  Environmental temperatures are important to maintain the pig within an equitable temperature range which is called the thermoneutral zone (the range between the upper and lower critical temperature as shown in fig 2.1.1. Within the zone, the heat production of the pig is independent of air temperature, and is determined by the pig's liveweight and feed intake.

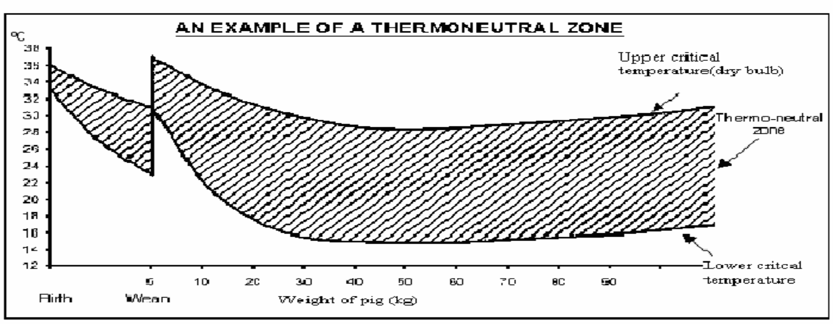


Figure 2.1.1: An example of a thermoneutral zone.

If the temperature of pigs is below the LCT, the pigs need to use some of their food to maintain body heat. Older pigs have lower LCT because they can stand lower temperatures for short periods without affecting their health, but food conversion efficiency will suffer.

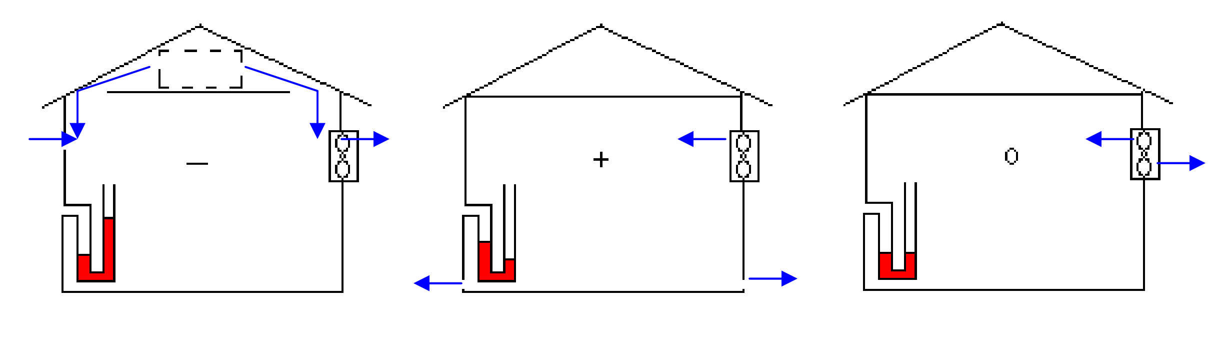
If the temperature is above the UCT, pigs become severely distressed. The UCT declines with increasing age of pigs. Temperatures much above 27°C are considered undesirable for pigs. However, if there is sufficient air movement at pig level, heat stress in dry climates can be reduced with the use of drip or spray cooling. The resulting evaporation of water from the pig's skin can effectively remove excessive body heat. This sort of evaporation, as well as the evaporation associated with panting, becomes less effective as humidity of shed rises. This why fogging sheds with water vapour is usually not recommended (Moore, 1994). In order to provide thermal comfort zone in pig housing, ventilation system is important for.

- **Ventilation**

Every pig continuosly gives off heat, moisture and carbon dioxide. In addition, urine and feces add gasses and microorganisms to the air, and pigs shed minute skin particles. When a pig is kept outdoors, these contaminants are quickly diltued into the atmoshere. Inside the pig housing, however, the comtaminants will continusouly accumulate unless they are removed. Therefore, ventilation is required in pig housing in order to remove heat, water vapour, carbon dioxide, ammonia, airborne dust, bacteria and odours.

Mechanical ventilation system provides protection for the pigs from extreme fluctuations in outdoor climate. Fan combined with properly planned air inlets provide the required fresh air to the barn. Very good control of the climate can be achieved with mechanical ventilation and is especially suited for younger pigs (Moore, 1994.). Different types of mechanical ventilation system will now be briefly discussed.

Types of mechanical ventilation systems**:** Air is exchanged in mechanical ventilated pig faclities due to the air pressure difference between the inside and outside of the pig housing. The pressure difference is generated by the use of fans. The most common system is shown graphically in figure 2.1.2:



A (Negative) B (Positive) C (Neutral)

Figure 2.1.2: Types of mechanical ventilation systems based on static pressure.

(Figure A)

The exhaust fan(s) create a slight negative pressure or vacuum in the barn, which causes air to enter the barn through designed inlets. This system is commonly used in livestock housing and will be discussed in more detail in chapter 4.

(Figure B)

Fans blow air into the barn creating a positive pressure and air escapes through designed outlets.

(Figure C)

Push-pull system operates under neutral pressure at continuous or cold weather ventilating rates. Fans create a zero or approximate neutral pressure difference between the inside and outside of pig housing (Larry, 2001.).

2.2 Design and management considerations for piggery

- **Orientation of buildings**

-Space:

Building costs oblige space per pig to be limited to levels which will not impair the welfare or performance of the animal. Table 2.2.1, with values taken from Model Code of Practice for the welfare of pigs, provides a guide for minimum space allotment in addition to that required for laneways (Moore, 1994.).

Table 2.2.1: Minimum space requirements using partially or fully slatted pens

Description	Space (m^2/pig)
Growing pigs up to 10 kg	0.11
11-20 kg (Weaner)	0.18
21-40 kg (Weaner)	0.32
41-60 kg (Grower)	0.44
61-80 kg (Finisher)	0.56
81-100 kg (Combined)	0.65

-Hygiene:

Poor ventilation in pig housing affects hygiene. By increasing the air flow through piggery, many airborne particles, which include clumps of micro-organisms, will be removed. This will improve the air quality inside the building, reducing the risk of respiratory disease. Bad ventilation can also lead to high humidity and poor air quality, resulting in bad dunging patterns, which further reduce the level of hygiene. Overcrowding, especially in hot humid weather, also lowers hygiene rates (Moore, 1994.).

CHAPTER THREE

LITERATURE REVIEW

This chapter summarizes work reported in the open literature and provides an overall understanding on the numerical studies of ventilation of pig housing. The knowledge obtained from the review will be used as guidelines for the CFD simulations.

(Randall*, 1980*) investigated the distribution of the cooling effects for a number of penning layouts and traditional straight-through ventilation systems using a full scale experimental rig. The best recommended layout was a building having a central feeding passage and side dunging passages, without any partition between the lying and dunging areas, combined with a ventilation system in which air enters horizontally in both directions at the ridge at a speed of 4 to 5 m/s beneath a smooth ceiling. This layout can provide a good air mixing, a stable airflow pattern, a degree of control over the influence of wind on ventilation rate and good air environment in hot weather.

(Mossad, 2001) performed numerical modeling of air temperature and velocity in a forced and free ventilation piggery to achieve optimum environmental control. A steady two-dimensional numerical model including the effect of buoyancy, turbulence and heat generated by the pigs was solved using the CFD software FLUENT. The cases investigated were: one side inlet which is opposite to the extraction fan, two sides inlet and centered inlets in the ceiling and two weather conditions i.e. winter and summer where outside temperatures were taken as 5°C and 32°C, respectively. It was found that one side inlet provided a better air mixing inside the piggery and to offer air distribution within the thermal comfort zone in summer for weaning pigs. The model results suggested that for winter, heating has to be used to bring temperatures to within the pigs' thermal comfort zone.

(Lee et al., 2004) investigated the visualization of internal airflow for force ventilation of piggery with perforated ceiling, a very popular arrangement in Korea. They found out that in compartment without animals, CFD result showed that maximum velocities at piggery was 0.06, 0.55 and 0.95m/s for 5, 50, and 100% of ventilation settings, respectively. Very poor environmental conditions were found at both end wall areas compared to the other areas of the compartment caused by the dilution of internal relative humidity of the time-dependent CFD model.

(Wu & Gebremedhin, 2002) evaluated turbulence models for predicting flow fields in a multi-occupant ventilated space. Five different turbulence models were evaluated in order to establish the most appropriate model for ventilated spaces in animal housing. Based on convergence and stability criteria, the RNG k-ε model was found to be the most appropriate model for the application considered.

(Li et al., 2004) studied the effect of the ventilation system design on the flow pattern and the contaminant distribution for different combinations of ventilation rate and recirculation rate. The three-dimensional flow structure, the contaminant concentration and temperature at the human breathing line were highly affected by the combined jets of a ceiling inlet jet and a recirculation slot jet. The placement of the ceiling inlet and the recirculation duct affected airflow patterns, but had only a slight effect on the distribution of velocity, temperature and ammonia concentration along the human breathing line. The optimum ratio of the ventilation rate to the cleaned recirculation rate was found to be approximately 1:4.

(Bjerg et al., 2002) investigated the effects of pen partitions and thermal pig simulators on airflow in a livestock test room by measurements and CFD simulations. Four guiding plates were mounted beneath the ceiling in the test room to obtain two-dimensional flow in the occupied zone. Three arrangements for the experiments were: (a) the room with guiding plates; (b) the room with guiding plates and eight heated pig simulators; and (c) the room with guiding plates, eight heated pig simulators and 0.8m high partitions which divided the room into four equal-sized pens. Both measurements and CFD simulations showed that the introduction of pen partitions and thermal pig simulators reduced the air velocities in the occupied zone of the test room. They commented that k-ε turbulence model was not able to predict accurately the re-circulating zones.

(Bjerg et al., 2002) investigated different methods to model wall inlets in CFD simulations of airflow in livestock rooms. Experiments were conducted in a test room with the dimensions 8.5m length, 3 m height and 10.14 m width. The test room was equipped with forced ventilation system. Four wall inlets were distributed symmetrically along an end wall 0.5 m beneath the ceiling. The inlets were designed as a rectangular frame with an elliptic profile in the contraction section following the ISO standard for a long-radius nozzle to obtain uniform and easily modeled boundary conditions. Thermistor speed sensors at four distances from the inlets were used to measure the vertical and horizontal air speed profiles in the jets and ultrasonic sensor was used for measurement of air velocity in the occupied zone close to the floor. CFD simulations with the k-ϵ turbulence model were carried out with a number of different grid constructions. Both measurement and CFD simulations showed that two different airflow patterns occurred in the test room. The outcome of this study indicated that assuming two dimensional (2-D) inlet conditions might be a useful way to simplify inlet boundary conditions and grid constructions for prediction of air flow in the livestock rooms with many wall inlets.

CHAPTER FOUR

MODEL HOUSING

In this chapter, the pig housing shown in figure 4.1 was modeled by using Pro-Engineer student edition 2001. The pig housing has 12 fully slotted pens, 6 on each side of middle alley connected with a door to a side corridor. The size of the pig housing compartment was 22 m length, 4.5 m height and 12 m width. This will house approximately a total of 150 pigs of growers and finishers type. Figures 4.2 and 4.3 showed the detail drawings and the isometric view of the pig housing, respectively. Figure 4.4 shows the floor plan of the pig housing. Each pen is of dimensions 2.4 x 5 m, or 12 m^2. This handles 25 pigs at an area of 0.54 m^2 per pig. The ventilation system is a forced extraction fan type with four stages. The floor is fully slotted and air inlet will be at both side walls. The ceilings are insulated with 0.1 m plaster board, the roof is made of corrugated steel sheet, the external walls are made of common brick, and the floor and a central walkway are concrete. Six different arrangements of the size, position and numbers of the air inlets and outlets were set up.

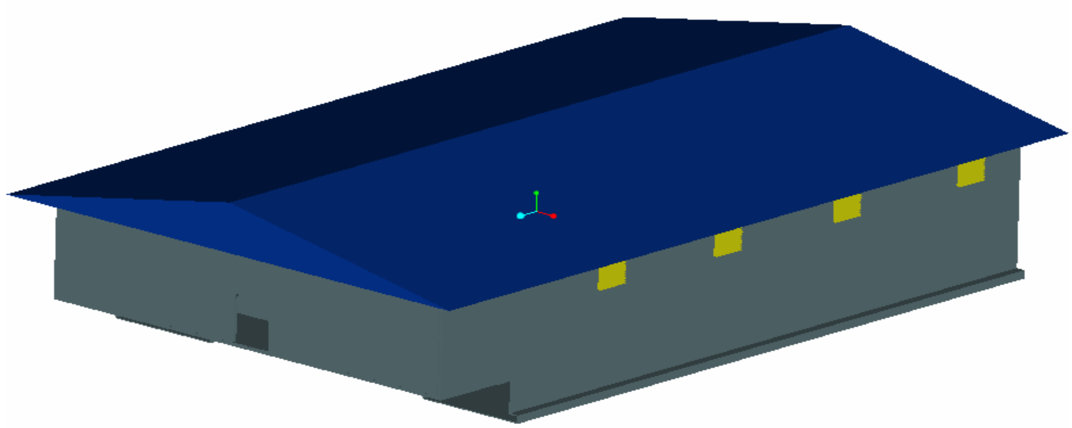


Figure 4.1 Typical building of pig housing

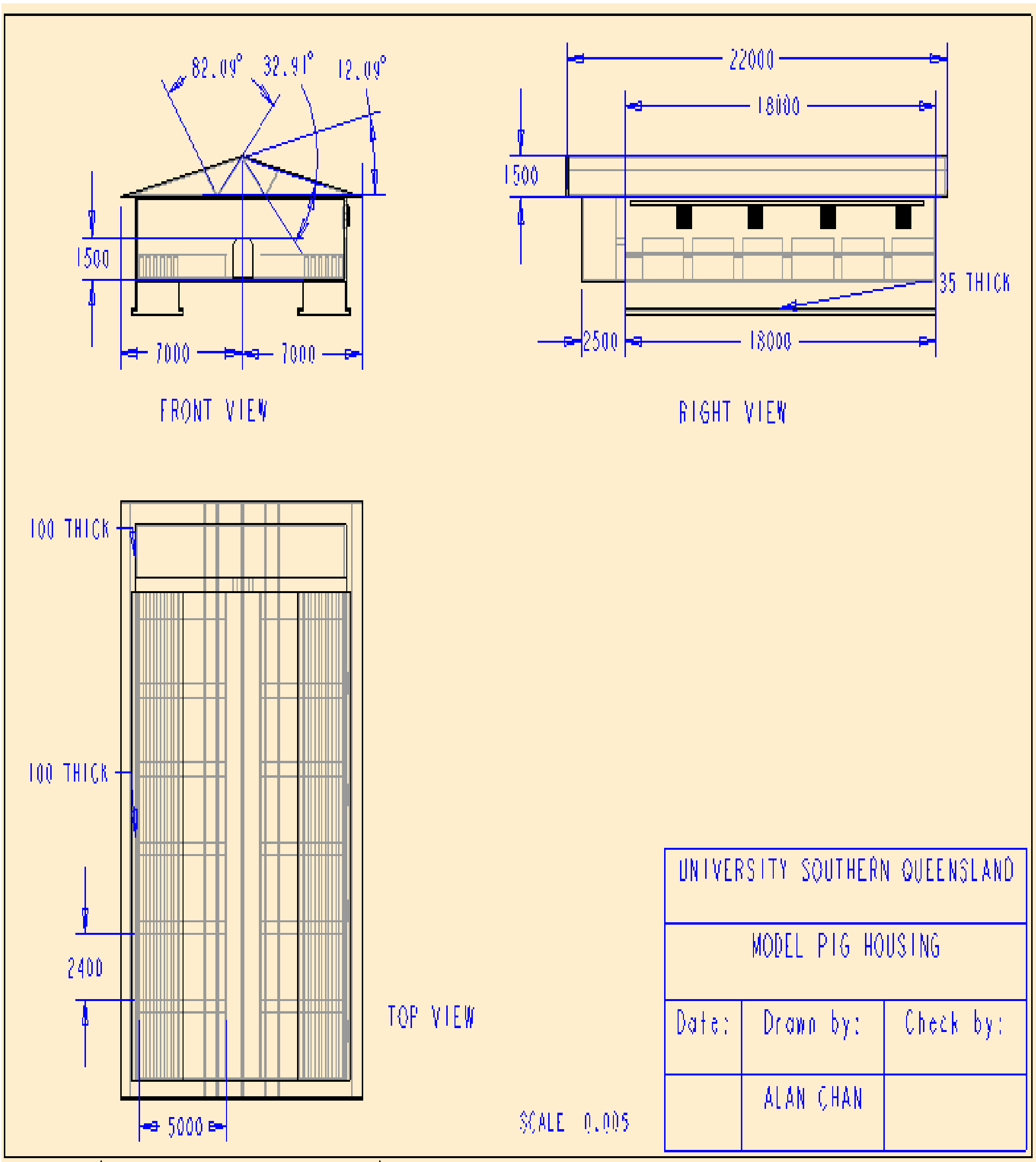


Figure 4.2 Detail drawing of the pig housing used in this study.

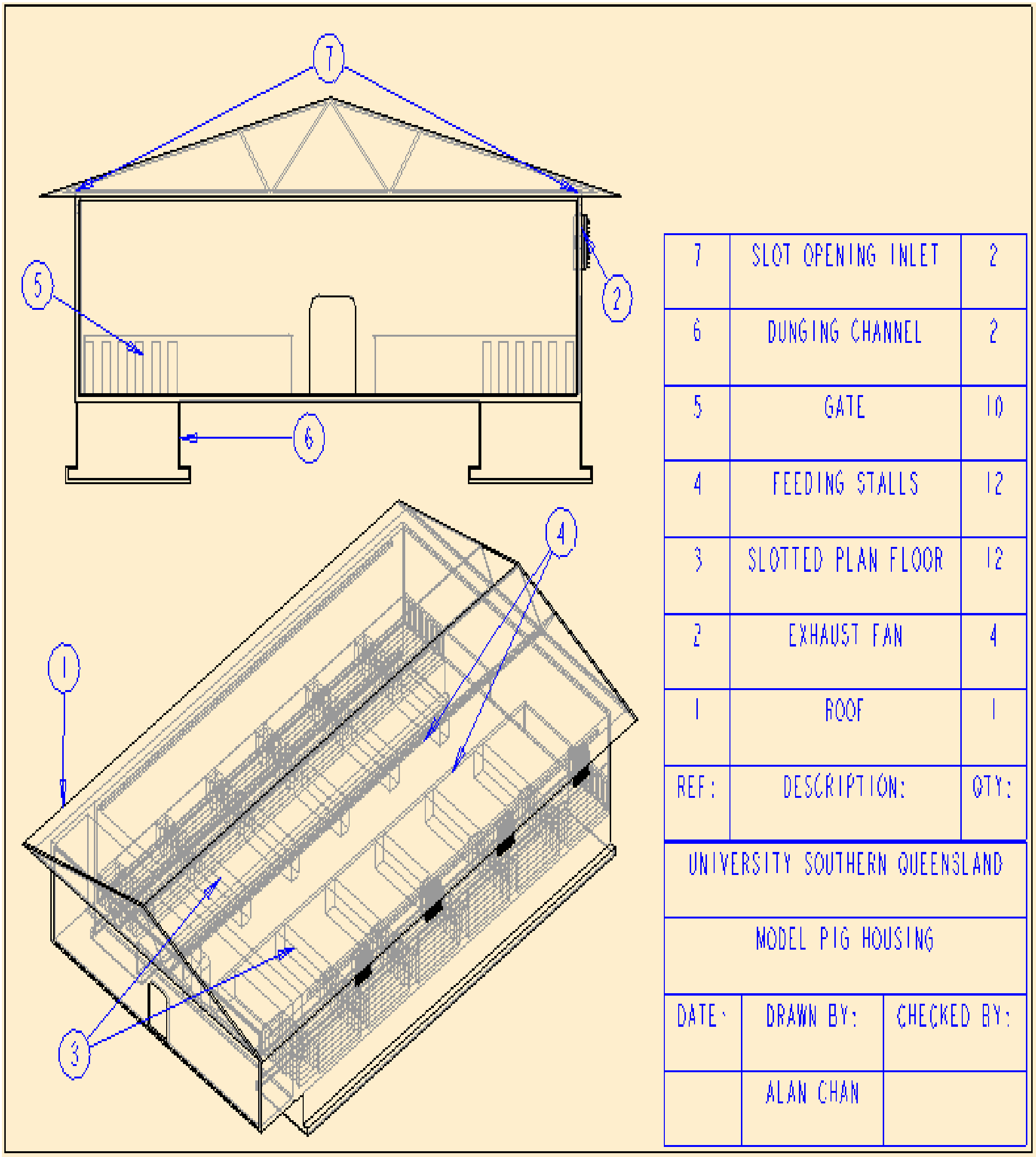


Figure 4.3 Isometric view of the pig housing used in this study.

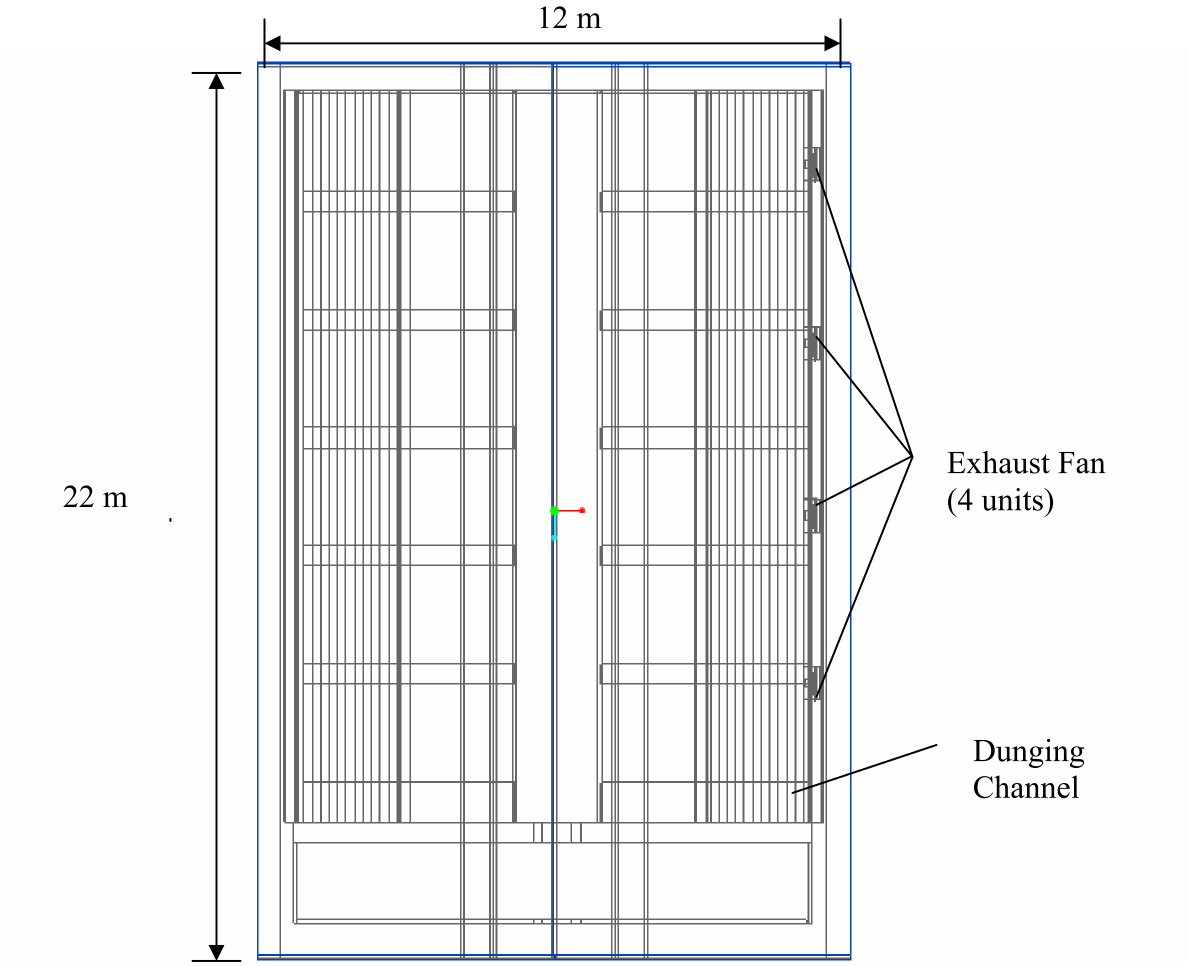


Figure 4.4 Floor plan of the pig housing used in this study.

All inlets were taken to be silt with full length of the side wall, the narrow gap between the baffle and the ceiling creates the jet that is the basis of the ventilation systems. In this study, the side wall opening will be referred to as the air intake, while the air discharge gap between the baffle and the side baffle will be referred to as the inlet (see figure 4.5). Exhaust fans in one side of the wall create the pressure differential necessary for the desired fresh air exchange rate. The effect of different widths, air speed position and number of inlets and outlets on air flow pattern is studied.

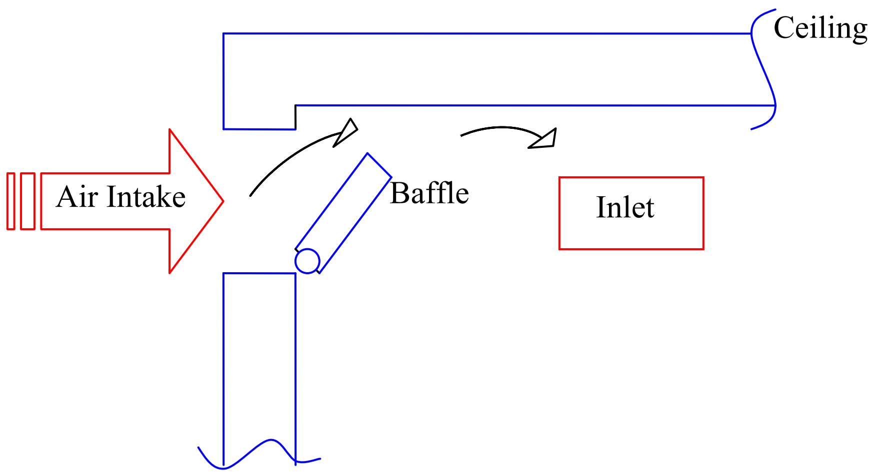


Figure 4.5 A schematic diagram of air intake and inlet.

4.1 Six different arrangements

Figures 4.1.1 to 4.1.6 showed six different arrangements to be investigated in this study, i.e. with different size, position and numbers of inlet width and outlets. The investigation was carried out by assuming a rectangular shape test room equipped with a forced ventilation system. Main dimensions of the section are: width 12 (x-direction); side wall height, 3m (y-direction); maximum distance from floor to ceiling, 3m (y-direction); inlet width, 0.05m (y-direction) and exhaust fan diameter, 0.2m (y-direction).:

- Room with two inlets (width = 0.05 m) and one outlet (Ø0.2 m)

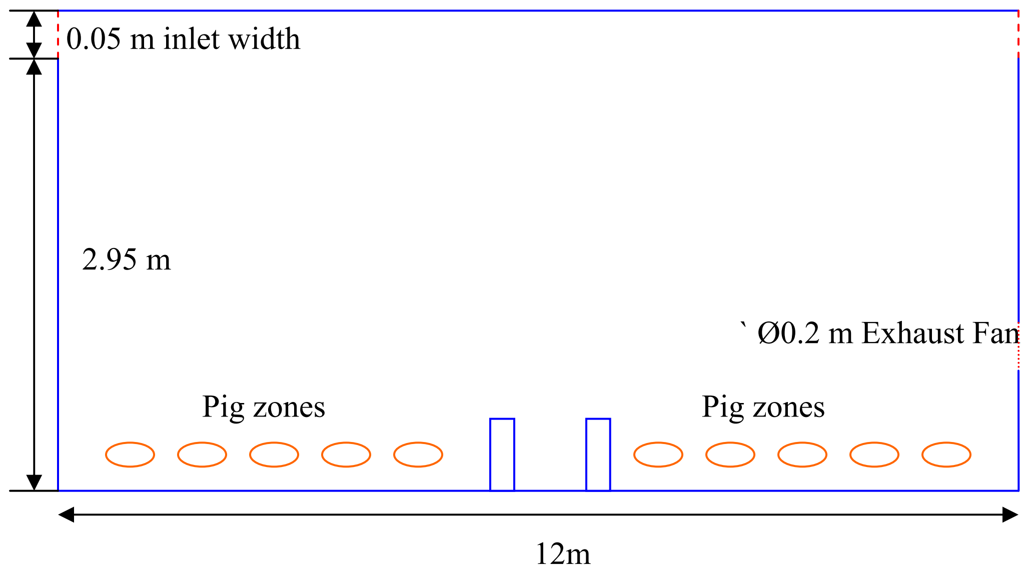


Figure 4.1.1 Arrangement of two inlets (width = 0.05m) and one outlet.

- Room with two inlets (width = 0.2 m) and one outlet (Ø0.2 m)

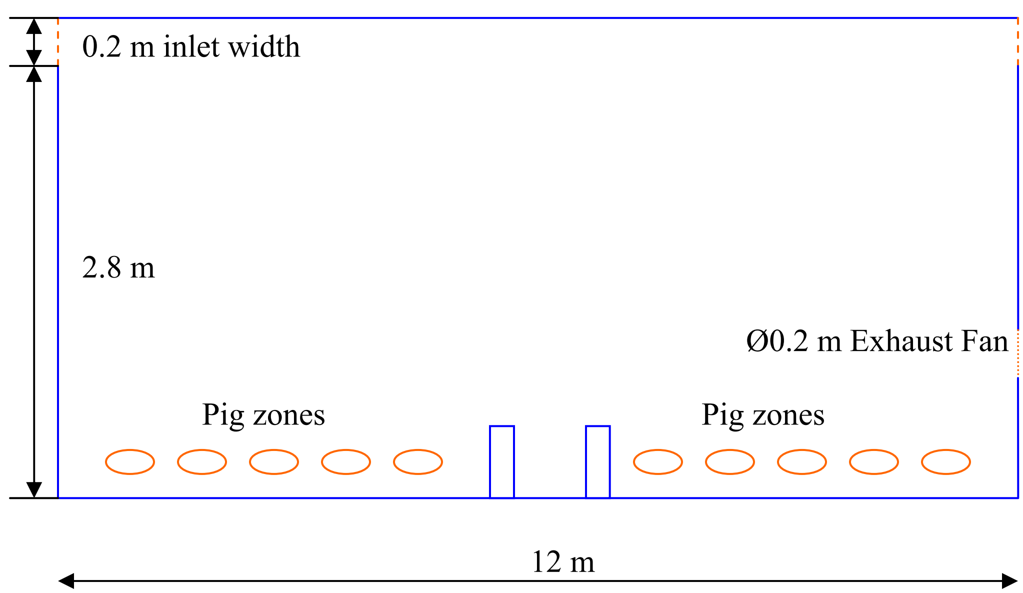


Figure 4.1.2 Arrangement of two inlets width at 0.2 m and one outlet

- Room with two inlets (width = 0.05m) and two outlets (Ø0.2 m)

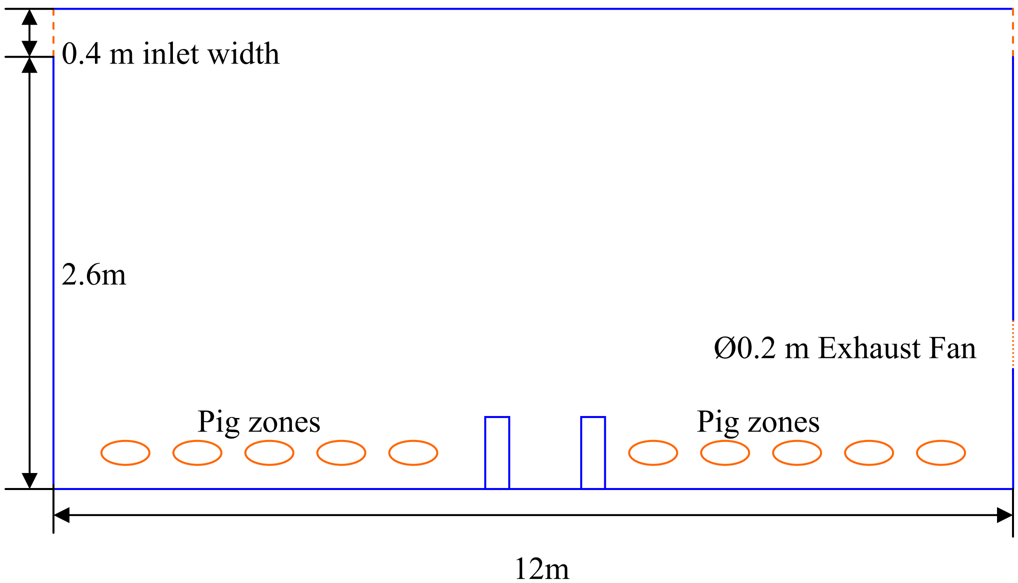


Figure 4.1.3 Arrangement of two inlets width at 0.4 m and one outlet

- Room with two inlets (width = 0.05m) and two outlets (Ø0.2 m)

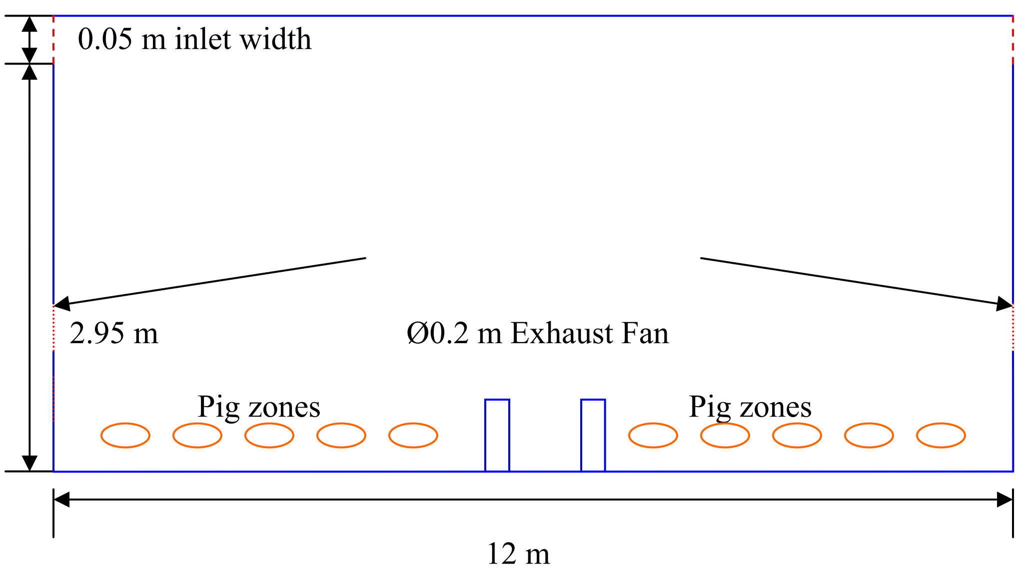


Figure 4.1.4 Arrangement of two inlets width at 0.05 m and two outlets.

- Room with two inlets (width = 0.2 m) and two outlets (Ø0.2 m)

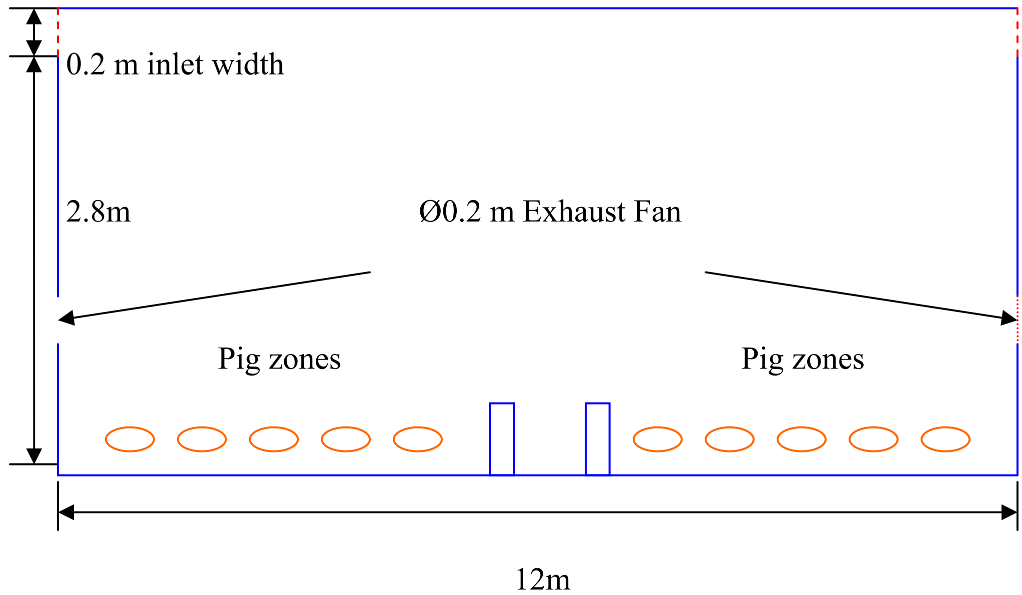


Figure 4.1.5 Arrangement of two inlets width at 0.05 m and two outlets

- Room with two inlets (width = 0.4 m) and two outlets (Ø0.2 m)

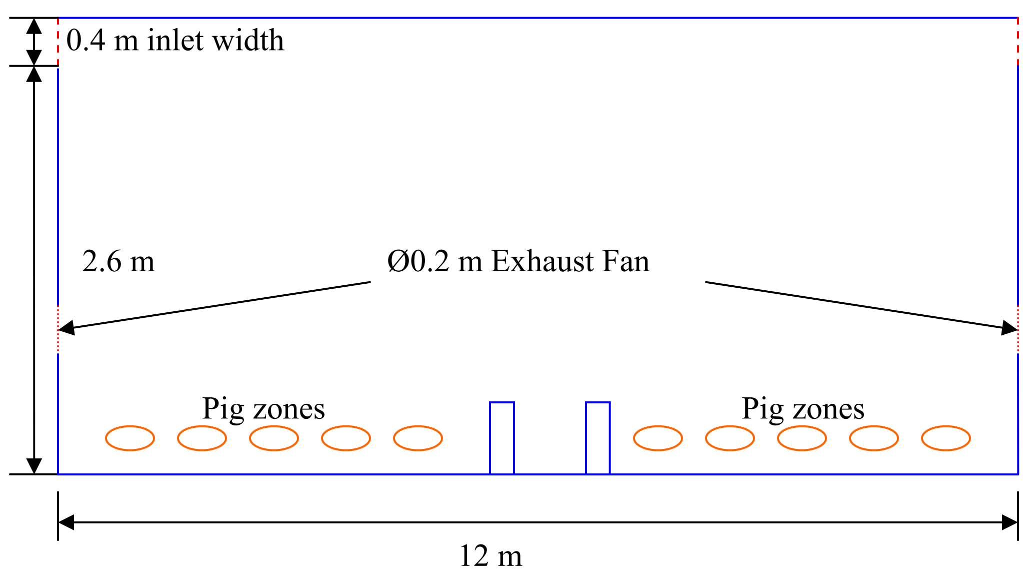


Figure 4.1.6 Arrangement of two inlets width at 0.4 m and two outlets

CHAPTER FIVE

MATHEMATICAL MODEL

In this chapter, mathematical models used in CFD will be discussed and the governing differential equation, solution technique used in FLUENT related to the present study are also described**.**

5.1 Transport equations

The equations that describe the flow of a fluid and heat within an enclosure are based on the conservation of mass, momentum and thermal energy (Hazim, 2003.). The equations take the form of partial differential equations (PDEs). Each PDE describes the conservation of one dependent variable within the field. Two dimensional (2D) models are used in this study. The two dimensional (2D) incompressible, steady and turbulent flows in the x-y-plane with heat generation are modeled. The PDEs used in this study is in the form of Cartesian coordinate systems (i.e. x and y). The velocity and temperature profiles are predicted by solving the PDEs.

The conservation of mass of a steady and incompressible flow within the control volume dx and dy is given as:

- (Continuity equation)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (5.1)$$

By applying the law of conservation of momentum (i.e. the net force on the control volume in any direction equals the efflux of momentum minus the influx of momentum in the same direction.) in the x and y directions:

- Momentum equation (Navier-Stokes equations)

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$u\frac{\partial v}{\partial x}+\mathrm{v}\frac{\partial u}{\partial y}=g\beta\left(T-T_\infty\right)-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 \mathrm{v}}{\partial x^2}+\frac{\partial^2 \mathrm{v}}{\partial y^2}\right) \qquad (5.2)$$

The conservation of thermal energy in the control volume dx and dy describes that the net increase in internal energy in the control volume equals the net flow of energy by convection plus the net inflow by diffusion and also heat generation:

- (Energy equation)

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{q}{\rho c} \qquad (5.3)$$

where u, v, p, and T are the average velocities in x and y directions, average pressure and temperature, respectively; while ρ, v, β, α, c, q and g are density, kinematics viscosity, coefficient of thermal expansion, thermal diffusion coefficient, specific heat, rate of heat generated by the pigs/unit volume and acceleration of gravity, respectively.

Although numerical predictions using computational fluid dynamics (CFD) are becoming more widely acceptable in design, experimental data obtained from physical model studies are still considered as the most reliable source for the design**.** Before conducting an experimental investigation involving a physical model it is essential that the fundamental similarity laws relevant to the case under investigation be established and implemented during the experiments. Any deviation from the basic laws of similarly pertaining to the physics of the problem could minimize the significance of the results obtained from the model tests.

5.2 Dimensional analysis

Dimensional analysis was used to ensure that the values of parameters measured in the test model will accurately reflect the properties of real pig housing. Dimensional analysis is a powerful tool in physical model studies. In developing a complex model, the physical properties of a prototype must be symmetrically scaled to their equivalent model values. Table 5.2.1 lists 15 parameters that have been chosen for the dimensional analysis study.

Table 5.2.1 Parameters, symbols and units used in the dimensional analysis.

Parameter	Symbol	S.I units	Fundamental
Thermal conductivity (air)	k_a	$Wm^{-1}K^{-1}$	$MLT^{-3}\theta^{-1}$
Thermal capacity	Q	W	ML^2T^{-3}
Time	t	s	T
Spec. heat capacity (air)	C_a	$Jkg^{-1}K^{-1}$	$L^2T^{-2}\theta^{-1}$
Density (air)	ρ_a	kgm^{-3}	ML^{-3}
Internal dimensions, Length	L	m	L
Internal dimensions, Width	W	m	L
Internal dimensions, Height	H	m	L
Hydraulic diameter	D_h	m	L
Materials thickness of wall	X_w	m	L
Materials thickness of ceiling	X_c	m	L
Materials thickness of floor	X_f	m	L
Velocity	V	ms^{-1}	LT^{-1}
Heat generation	q	W/m3	$ML^{-1}T^{-2}$
Dynamics viscosity	μ	Ns/m^2	$ML^{-1}T^{-1}$

The thermal response of the enclosure can be expressed in the following relationship:

$$Q_{net}=f(k_a, V, q, \ldots L, W, H, X_w, \ldots) \quad (5.4)$$

Because of their importance, the thermal conductivity of air, velocity, density of air and hydraulic diameter are chosen as independent variables, The Buckingham's π-theorem states that the number dimensionless groups is equal to the number of variables minus the number of independent variables. Thus, 11 dimensionless groups can be obtained. Similarity between the prototype and model exists if the model parameters are such that:

$$\pi_{\text{model}} = \pi_{\text{prototype}} \tag{5.5}$$

The set of 11 dimensionless groups is as listed in table 5.2.2.

Table 5.2.2 Dimensionless groups of 11 equations

Dimensionless groups	
π_1	$\dfrac{Q}{\rho_a V^3 D_h^{\;2}}$
π_2	$\dfrac{Vt}{D_h}$
π_3	$\dfrac{V\rho_a C_a D_h}{k_a}$
π_4	$W(D_h)^{-1}$
π_5	$L(D_h)^{-1}$
π_6	$H(D_h)^{-1}$
π_7	$X_w(D_h)^{-1}$
π_8	$X_c(D_h)^{-1}$
π_9	$X_f(D_h)^{-1}$
π_{10}	$\dfrac{q}{V^2 \rho_a}$
π_{11}	$\dfrac{\mu}{\rho_a V D_h}$

Therefore, the functional relationships are:

π_1 (for Q) = function of all the other π's

π_2 (for t) = function of all the other π's

It is noted that the exact functional relationship among the π parameters must be determined experimentally. However, this is beyond the scope of this study.

5.3 Numerical method

Examples of CFD programs that can be used to predict the air flow pattern in the pig housing are PHOENICS, FLUENT, VORTEX. In this study, FLUENT software was used to solve the above equations. FLUENT uses equations that are discretised on a curvilinear grid to enable computations in a complex domain.

An inlet velocity range from 1 ms^{-1} to 5 ms^{-1} with 5% to 10% turbulence intensity and wall functions at all surfaces were used in all the simulations. The effect of turbulence was taken into account by k-ε turbulence model. This is widely used in two-dimensional model based on transport equations for turbulent kinetic energy and the dissipation of turbulence kinetic energy. Figure 5.3.1 presents the simulation of two dimensional models which housed about 24 pigs in x-y plane in FLUENT.

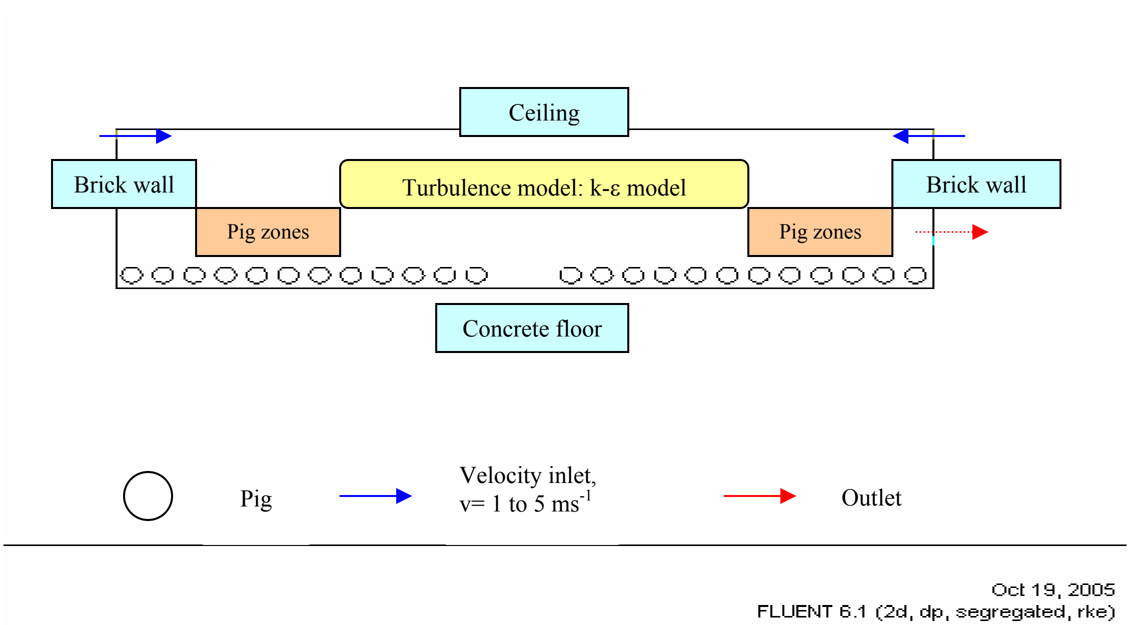


Figure 5.3.1 CFD model set up in FLUENT

Interpolation of the CFD model is accomplished via a first order upwind scheme. When the segregated solver is used, all equations are solved using the first-order upwind discretization for convection. The equations are solved using a semi-implicit algorithm with an interactive line by line matrix solver and multi-grid acceleration. In FLUENT, there are some important parameters to be considered. For example, the model has to enable heat transfer energy due to heat generated by pigs. The fluid flow inside the model was incompressible flow with constant air properties. Boundary condition is important parameters that need to be carefully selected. Since different parts of the pig housing experienced different wind velocity and sunshine, the heat coefficient of the outside wall vary with time. Floor surfaces are concrete with a constant temperature which is 2 °C lower than the ambient temperature.

The ambient temperature was determined to be 30 °C and the inlet air speed varied from 1 to 5 ms^{-1}. The negative pressure ventilation system was applied in the model therefore the outlet flow as a exhaust fan have to create a static pressure (negative pressure) inside the model. This will ensure that fresh air is always brought inside the pig housing.

The k-ε model is adopted to describe the turbulence. Two k-ε models are considered and compared, i.e. the Standard k-ε model and the Realizable k-ε model. The theoretical explanation for these two turbulence models will be discussed later.

GAMBIT is used to help analysts and designers build and mesh models for FLUENT. GAMBIT receives user input by means of its graphical user interface (GUI). The GAMBIT GUI makes the basic steps of building, meshing, and assigning zone types to a model. It is simple and intuitive, yet is versatile enough to accommodate a wide range of modeling applications. The model housing is modeled and meshed for different location, size and number of inlets and outlets and the boundary conditions need to be defined before export to FLUENT.

5.3.1 Standard k- ϵ model & Realizable k- ϵ model

The Standard k- ε model is a semi-empirical model based on model transport equation for the turbulent kinetic energy (k) and its dissipation rate (ϵ). From derivation of the k-ε model, it was assumed that the flow is fully turbulent, and the effects of molecular viscosity are negligible therefore this model can only be used for fully turbulent flow. On the other hand, the 'Realizable' term means that the model satisfies certain mathematical constraints on the normal stresses, consistent with the physic of turbulent flows.

The model transport equation for k is derived from the exact equation and the model transport equation for ε was obtained using physical reasoning. Table 5.4.1.1 presents the turbulent kinetic energy, k, and its rate of dissipation, ε, for both turbulence models:

Table 5.4.1.1 Transport equations for Standard k- ε and Realizable k- ε models

Turbulence model	$C_{1\varepsilon}$	$C_{2\varepsilon}$	Cμ	σ_k	σ_ε
Standard k- ε $\rho\frac{Dk}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M$ $\rho\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_2\rho\frac{\varepsilon^2}{k}$	*1.44*	*1.92*	*0.09*	*1.0*	*1.3*
Realizable k- ε $\rho\frac{Dk}{Dt}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M$ $\rho\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b$	*1.44*	*1.9*	*0.09*	*1.0*	*1.3*

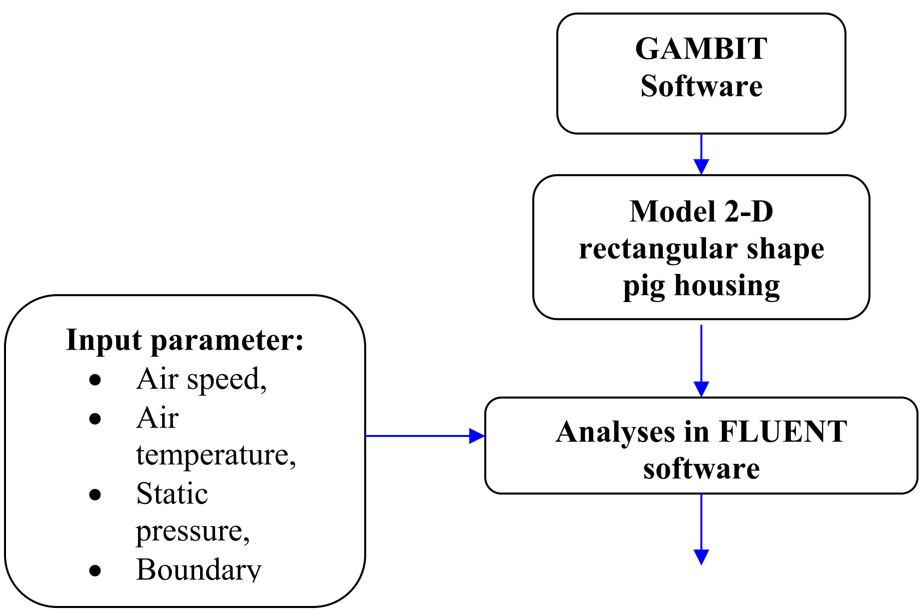
In these equations, G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients, G_b is the generation of turbulent kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively.

5.4 Flow chart of CFD analysis

Figure 5.4.1 presented the flow chart of the CFD model analysis. First, GAMBIT software was used to model and to mesh the two dimensional pig housing. The meshed model was then export to FLUENT.

Input parameters in FLUENT need to be determined carefully to provide accurate and reliable results. The initial values of the simulation model will influence the convergence of the simulation.

At each iterative step, the convergence of the numerical solution was checked. An iterative process is converged when further iteration will not produce any change in the values of dependent variables. The relaxation factors should be considered before determining whether or not a solution has converged. FLUENT provides guidance on how to determine the convergence of the solution via monitoring the residual value and the histories residual and solution variables.



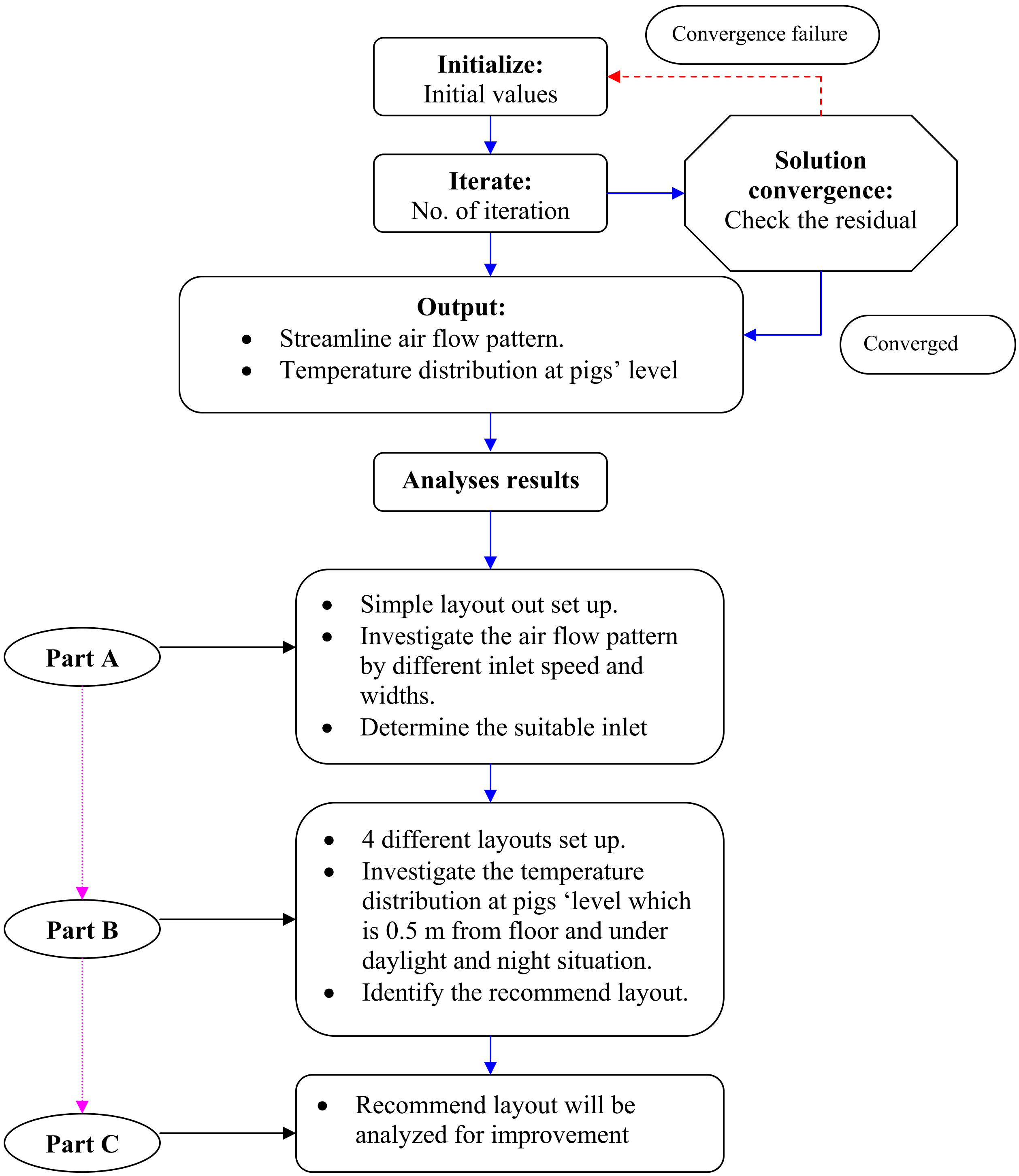


Figure 5.4.1 Flow chart of the CFD model analysis.

CHAPTER SIX

RESULTS AND DISCUSSION

Six different arrangements are simulated to investigate the effect of the inlet width and air speed at the side wall on the air flow pattern. Two different viscous models, i.e. the Standard k- ε and Realizable k- ε turbulence models were examined and compared. The discussions are divided into part A, B and C. In part A, the simulation will determine the optimum inlet width and air speed for the pig housing. Part B will consider the optimum design and investigate the velocities and temperature distribution at the pigs' level under daylight and night situation with different piggery layouts. Finally, part C presents some improvements in the layouts obtained from CFD simulations.

6.1 Result and discussions from CFD simulation

The thermal boundary condition on the external wall and roof were taken to be convection to the ambient temperature with heat coefficient $h_c = 10$ W/m^{2}K for wall, and $h_c = 2$ W/m^{2}K for roof, respectively. The temperature of the floor was taken at 2°C below the ambient temperatures. Velocities and temperatures at 0.5 m from the floor (i.e. at pig's level) were examined for a variety of inlet velocities ranging from 1, 2, 3, 4, and 5 m/s. Ventilation with different flow rates were analyzed (1.0m^3/s to 1.1m^3/s). At the velocity inlets the turbulence specification method was applied to intensity and hydraulic diameter and 10% assume the air is coming with some disturbance like on the windy side of the building and lower 5% assume the air is coming without much turbulence and take the hydraulic diameter as the width of the opening where the air is coming form. Streamlines of the flow pattern for analysis 1 (figure 6.1.1.1) & 2 (figure 6.1.1.2) were examined to investigate the effect of different inlets width and different inlet velocities on air flow pattern at the layout with two inlets at both sides' wall and one outlet at right hand side. Different turbulent model, Realizable k- ε was examined in analysis 2 (figure 6.1.2) to compare with the Standard k- ε model in analysis 1.

Analysis 1

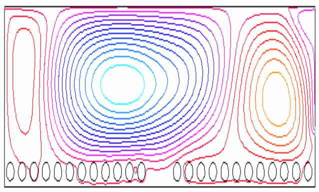
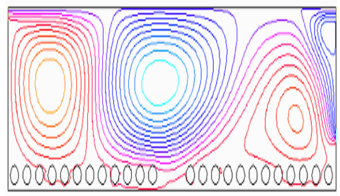
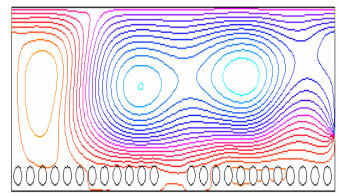
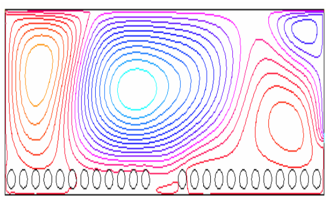
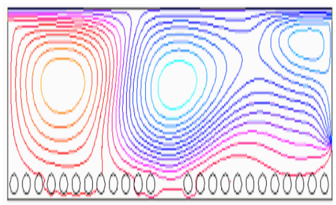
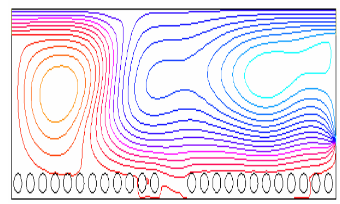
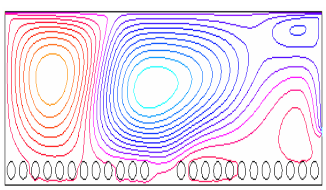
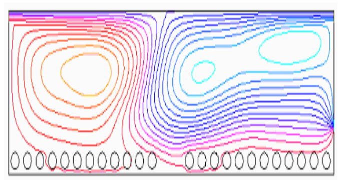
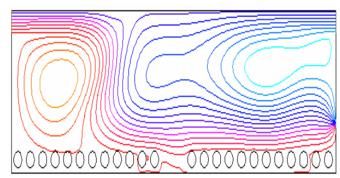
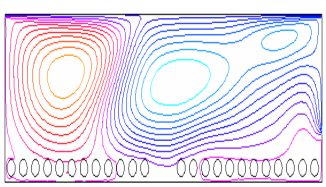
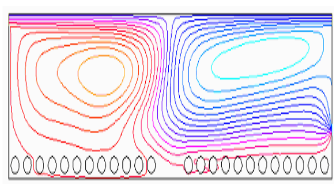
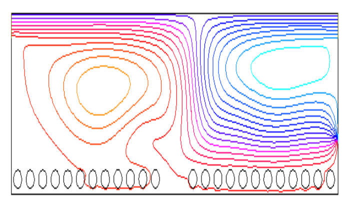
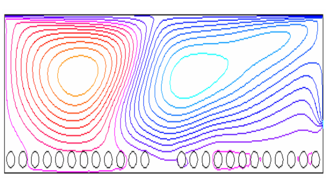
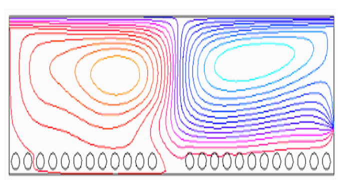
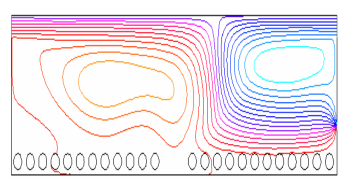
	Inlet width, (m)		
Velocity	*0.05*	*0.2*	*0.4*
1 m/s			
2 m/s			
3 m/s			
4 m/s			
5 m/s			

Figure 6.1.1.1: Two inlets and one outlet with different inlets width. (Standard k- ε)

Analysis 2:

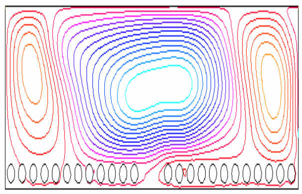
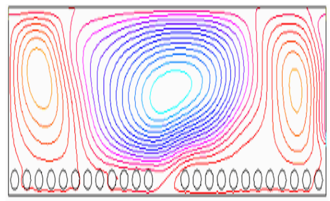
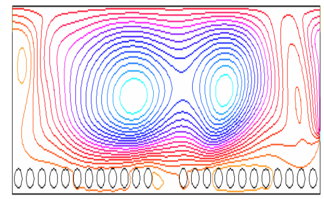
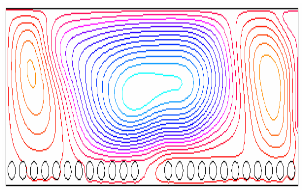
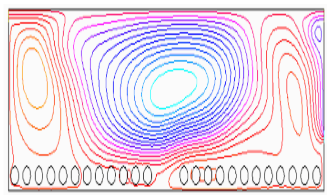
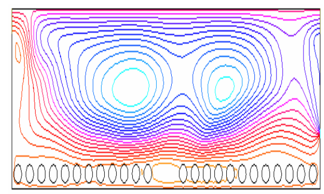
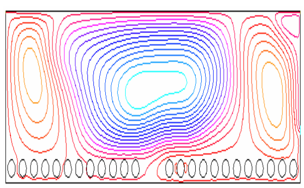
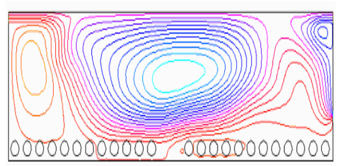
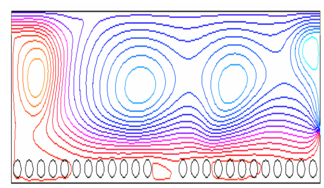
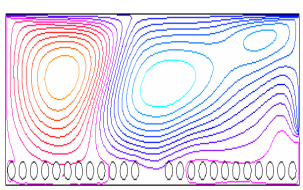
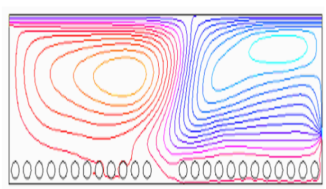
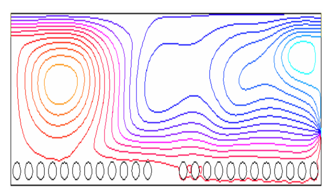
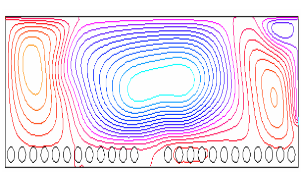
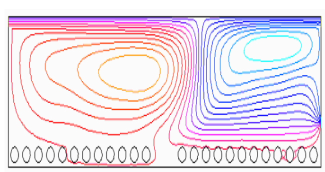
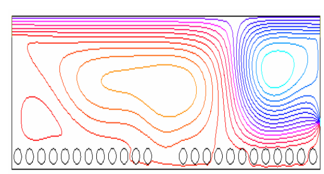
	Inlet width, (m)		
Velocity	*0.05*	*0.2*	*0.4*
1 m/s			
2 m/s			
3 m/s			
4 m/s			
5 m/s			

Figure 6.1.1.2: Two inlets and one outlet with different inlets width. (Realizable k- ε)

6.1.1 Part A: Effect of air flow pattern

Most of the cases produced a large circulation of air in the middle of the room. A large circulation of air is good mixing since it is mixing the air close to the roof with the air at the pig level. At the left hand side (L.H.S.), the fresh air mixes with air already in the room and dilutes the moisture, dust, gases, heat, and pathogens. This mixed air is then removed from the building by fans. However air from the right hand side (R.H.S.) seems to be short circuited and does not mix sufficiently with the room air to refresh the air in the housing. This is because the speed of the inlet air at the RHS is too small and the location of the inlet at the R.H.S is close to the exhaust fan. The inlet air at the RHS is drawn out very quickly by fan and therefore does not mix efficiently with room air.

Short circulation will form because there is very limited interchange of air between the primary circulation and secondary circulation zones. The inlet side of the housing will receive more fresh air, but the fan side will be under ventilated, particularly in the corners away from the fan. From analysis 1 & 2, it can be shown that, if the velocities are not high enough, the mixing air will not be removed outside the building by the exhaust fan. For example, there are very little differences between cases of velocity 1, 2, 3 m/s, especially for inlet width, 0.05 m and 0.2m. On the other hand, if the inlet air speed is more than 4 m/s, some cases i.e. inlet width 0.2m and 0.4m did not show short circuited flow at the R.H.S. Therefore, a high inlet air velocity is essential for providing good air mixing and desirable circulation patterns. Generally, analysis 1 and 2 performed using two different viscous models showed rather obvious differences. This is because the realizable k- ε model satisfies certain mathematical constraints on the normal stresses, and is consistent with the physics of turbulent flows. In contrast, standard k- ε model did not fulfill the mathematical constraints, and therefore is expected to be less accurate than the realizable k- ε model.

Basically, the exhaust fan extracts air from the housing, and the resistance to this air flow at the air entrance creates a static pressure difference between the inside and outside of the building. Fans provide air exchange by extracting mixed air and causing fresh air to enter the building. Analysis 3 & 4 investigated arrangements with two inlets and two outlets situated at each side of the wall. Streamlines of the flow pattern for analysis 3 (figure 6.1.1.3) & 4 (figure 6.1.1.4) were examined to investigate the effect of different inlets width and different inlet velocities on air flow pattern at the layout with two inlets at both sides' wall and two outlet at right hand side. Different turbulent model, realizable k- ε was examined in analysis 4 (figure 6.1.1.4) to compare with the standard k- ε model in analysis 3.

From the analysis, velocity of 1 and 2 m/s is not the desirable inlet velocity because in most of the cases investigated, bad circulation airflow is observed in the room as most of the air is not drawn out by fan. For 3, 4 or 5 m/s, the air flow pattern is better and the primary circulation involved in a general turnover, driven by one long thin air jet flowing across the ceiling and mix with the room air before being extracted out. Although analysis 3 for velocity of 3, 4 and 5 m/s suggested that the air flow pattern is symmetrical, the simulation results for similar setup produced by the realizable k- ε model gave an un-symmetrical air flow pattern (analysis 4).

Analysis 3:

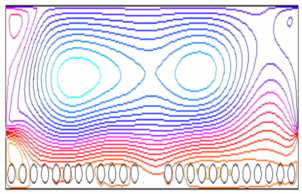
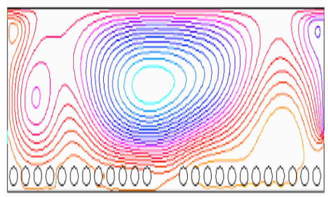
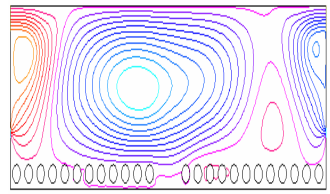
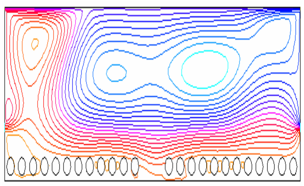
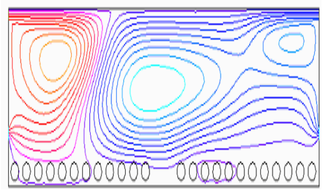
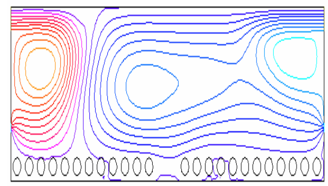
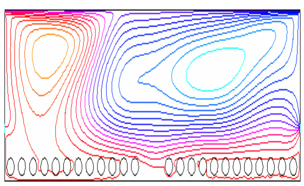
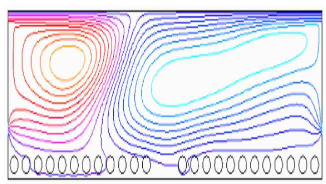
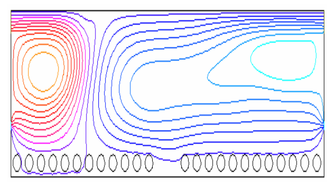
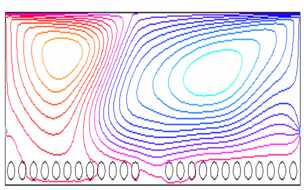
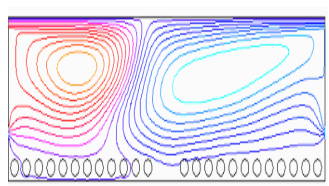
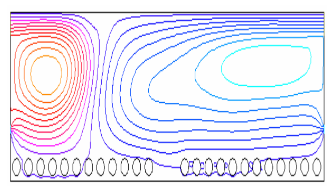
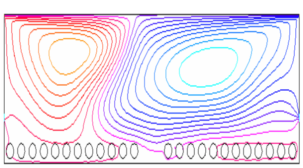
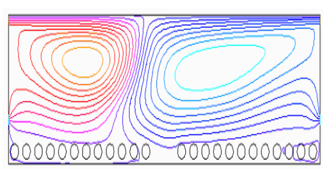
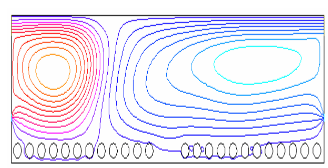
	Inlet width, (m)		
Velocity	*0.05*	*0.2*	*0.4*
1 m/s			
2 m/s			
3 m/s			
4 m/s			
5 m/s			

Figure 6.1.1.3: Two inlets and two outlets with different inlets width. (Standard k- ε)

Analysis 4:

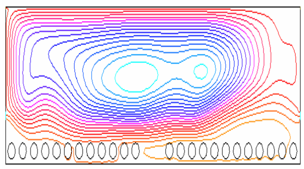
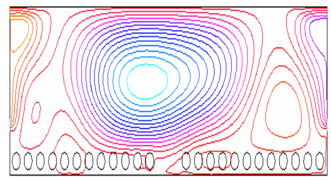
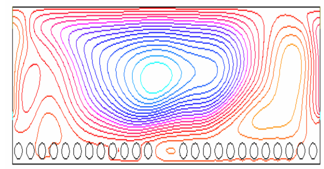
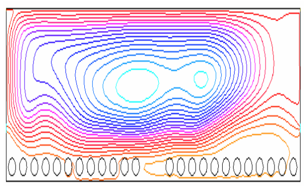
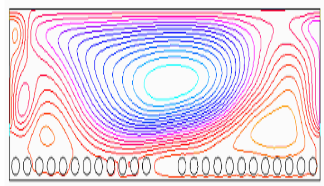
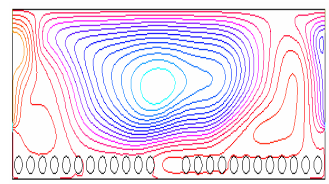
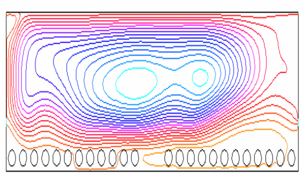
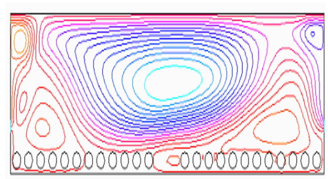
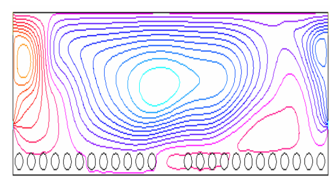
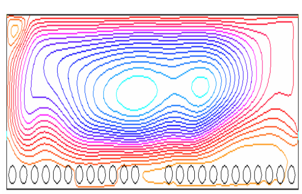
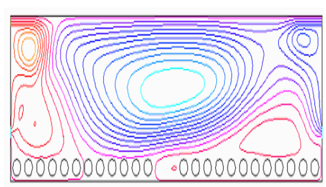
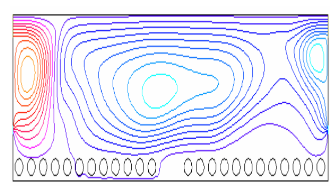
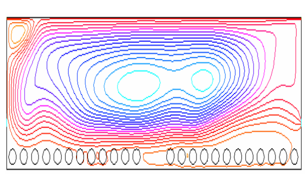
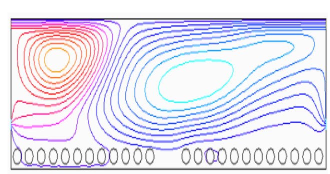
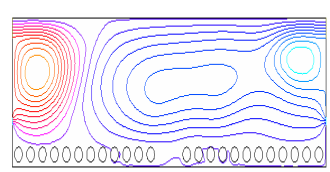
	Inlet width, (m)		
Velocity	*0.05*	*0.2*	*0.4*
1 m/s			
2 m/s			
3 m/s			
4 m/s			
5 m/s			

Figure 6.1.1.4: Two inlets and two outlets with different inlets width (Realizable k- ε)

As mentioned earlier, it is expected that the realizable k-ε model will provide a more accurate prediction as there are a lot of details were missing in the standard k-e model. For example, most of the cases show the air flow pattern could not produce a good mixing air in the room and clearly short circuiting flow occurred not only at the corners side of the wall but at the pigs' level too. The pigs' level will be filled up of moisture, dust and contaminants that cannot be taken out by fans. Therefore, the pigs will feel uncomfortable and affect severely its activities.

6.1.2 Part A: Effect of inlet width

The inlet widths may have a significant effect of introducing fresh air into the piggery. Small inlet opening does not allow adequate airflow or "throw" a jet of fresh air across the ceiling. The pigs may not feel comfortable which will resulted in poor conditions for pig. Especially, in realizable k- ε model a small inlet width and a low air velocity enter the housing does not help in the mixing of warm air. The big circulation flow continuous circulating in the middle of the room. This situation will produce a bad environment for the pigs living.

When inlet opening adjusted correctly by manually (workers have to adjust it), the incoming air accelerates to a speed that will throw a jet of fresh air across the ceiling. For example velocity at 4, 5 m/s in analysis 1 & 2, the circulation flow seems to be the best compared with the other cases. In this situation, the whole air space is involved in general turnover, driven by one long, thin air jet flowing across the ceiling. The throw of this jet is sufficient to reach almost half of building. Air exhausted by the fan is a fully mixed sample of the room air, and each volume of exhaust air removes its full share of moisture, dust and other contaminants. Besides, no dead air spot at the corners was formed.

On the other hand, analysis 3 & 4 produced better air flow pattern due to the high inlet velocity. In analysis 4, because of the realizable k-e model satisfies certain mathematical constraints on the normal stresses, consistent with the physics of turbulent flows therefore at essential inlet speed, v= 4m/s still produced dead air flow at the corners and pigs' level but when velocity increased to 5m/s finally the flow can assume better flow since incoming air does not travel directly to the exhaust fan but circulates in primary and secondary recirculation patterns before finally leaving through the fan.

When inlet width opens too wide, overall analysis did show the undesired flow pattern. Too wide opening directs airflow downward and form slow and lazy air stream. Although, in analysis 4, velocity at 4, or 5m/s, did form a good symmetrical flow pattern but inlet open too wide may cause the heavy cold air or lazy stream sinks unmixed to the floor, the lighter, warm room air is displaced upwards, and the two layers remain separated, a very unhealthy situation for sensitive animals penned at floor level.

According literature review, the recommendation ventilation rates for 24 pigs are in the range of 1.0 - 1.1m^3/s and the table 6.1.2.1 shown below gives the ventilation rates in housing which were caused by the different inlet widths and speeds. From the results, only inlet width 0.2m with inlet speed 5 ms^{-1} satisfies the recommendation rates of the pigs.

Table 6.1.2.1 Ventilation rates of the pig housing by different inlet widths and speeds

	Inlet width (m)		
Ventilation rates , Q(m^3/s)	0.05	0.2	0.4
Q with 1ms^{-1}	0.05	0.2	0.4
Q with 2ms^{-1}	0.1	0.4	0.8
Q with 3ms^{-1}	0.15	0.6	1.2
Q with 4ms^{-1}	0.2	0.8	1.6
Q with 5ms^{-1}	0.25	1.0	1.8

As the Realizable k- ε is able to predict more details than the standard k- ε model, therefore it is considered to provide more accurate results. In addition, research shows that an inlet speed of 4-5 m/s is enough to make the fresh air stream adhere to a smooth ceiling for a considerable distance across the room (Turnbull, 1999.). Therefore, inlet width of 0.2m at velocity of 4 m/s or 5 m/s in realizable model will be recommended for this study. However, analysis from part A not considers the temperature variation and it only consider in part B.

6.1.3. Part B: Velocities and temperature distribution

Important objective of the air distribution system is to create a comfortable thermal environment with proper combination of comfort variables such as air velocity and ambient temperature. Hence, to determine the best layout that offers a comfortable zone for the pigs, four layouts have been investigated. The distribution of temperature and velocity at 0.5m from the floor under daylight and night situation were predicted in the four layouts. These layouts and their corresponding streamlines are shown in figures 6.1.3.1 – 6.1.3.8. These layouts are as follows:

1. *Layout 1* (figure 6.1.3.1 & 6.1.3.2)

Two inlets slot at 2.8 m height at both side walls and one outlet which is located at the right hand side wall at a height of 0.8 m. The schematic diagram and streamlines are as shown in figures 6.1.3.1 and 6.1.3.2, respectively

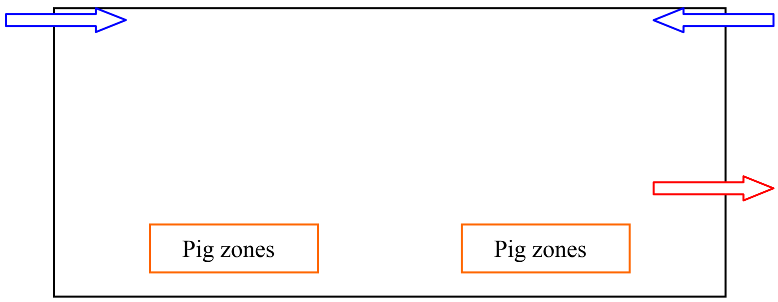


Figure 6.1.3.1: Arrangement of inlets and outlet for layout 1

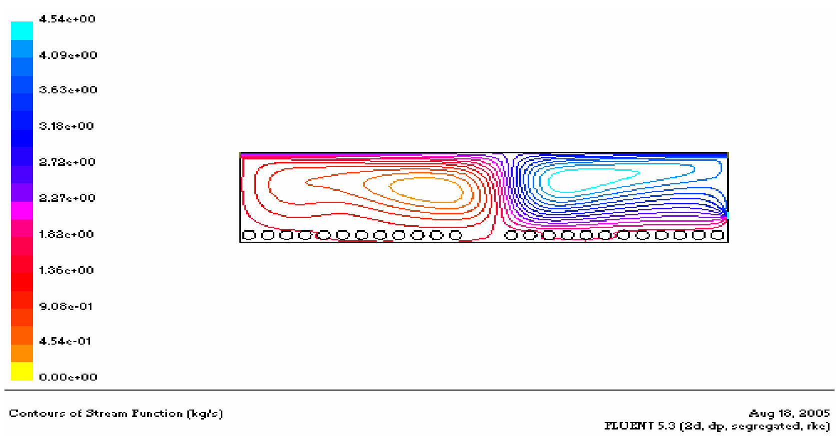


Figure 6.1.3.2: Streamlines for two inlets and one outlet Vin= 5m/s under daylight situation

2. *Layout 2* (figure 6.1.3.3 & 6.1.3.4)

Two inlets slot at 2.8 m height of both side walls and two outlets which are located at both side walls at 0.8 m high. The schematic diagram and streamlines are as shown in figures 6.1.3.3 and 6.1.3.4, respectively.

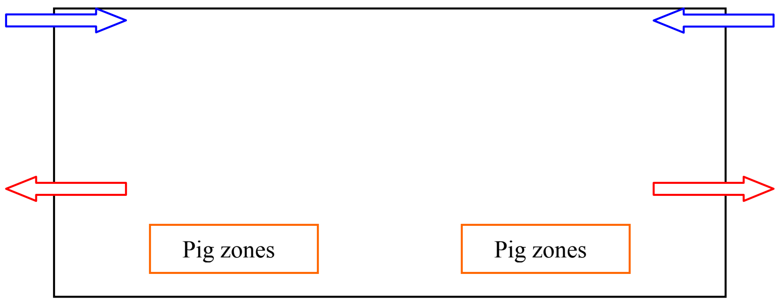


Figure 6.1.3.3: Arrangement of inlets and outlets for layout 2

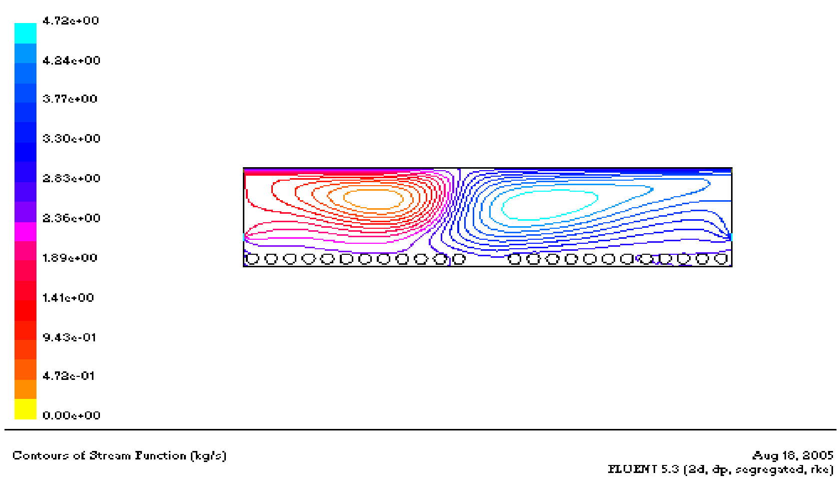


Figure 6.1.3.4: Streamlines for two inlets and two outlets case, Vin= 5m/s under daylight situation

3. *Layout3* (figure 6.1.3.5 & 6.1.3.6)

Two inlets slot at 0.8m and 2.8m height of (L.H.S) and two outlets at 2.8 m and 0.8 m height. (R.H.S). The schematic diagram and streamlines are as shown in figures 6.1.3.5 and 6.1.3.6, respectively.

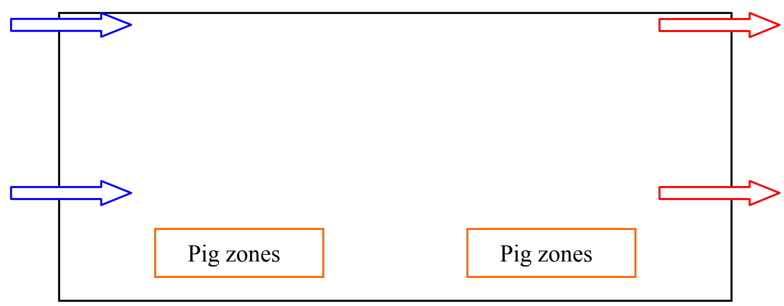


Figure 6.1.3.5: Arrangement of inlets and outlets for layout 3

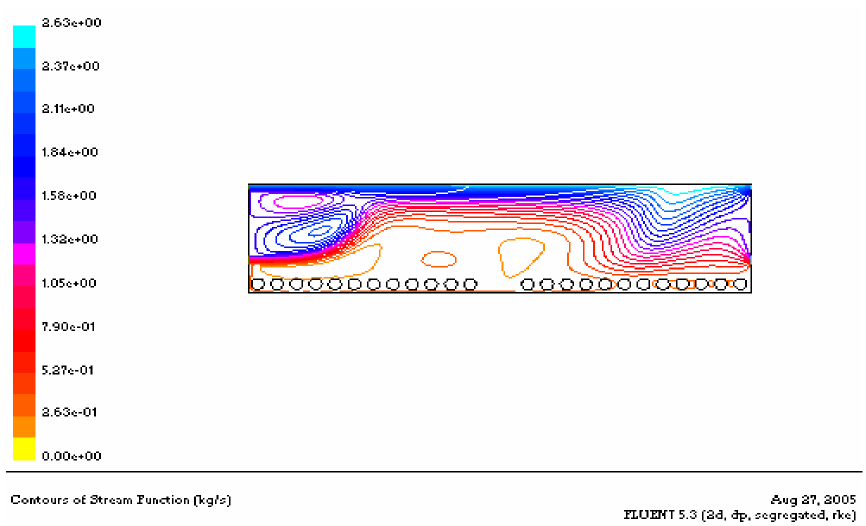


Figure 6.1.3.6: Streamlines for two inlets at L.H.S and two outlets at R.H.S; Vin= 5m/s under daylight situation.

4. *Layout4* (figure 6.1.3.7 & 6.1.3.8)

Two inlets slot at 2.8m of both side wall and two outlets which located at an open space below the floor at the corners of building. The schematic diagram and streamlines are as shown in figures 6.1.3.7 and 6.1.3.8, respectively.

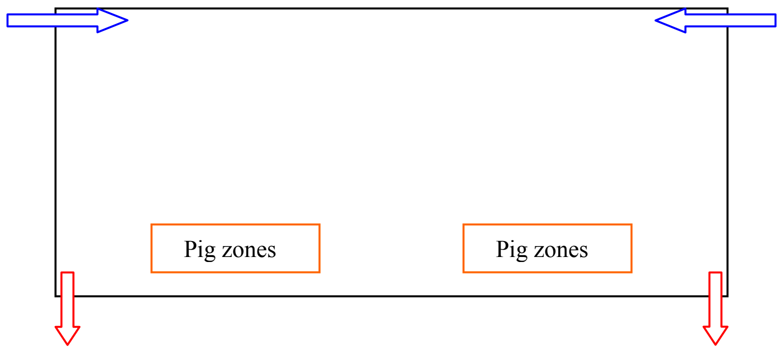


Figure 6.1.3.7: Arrangement of inlets and outlets for layout 4

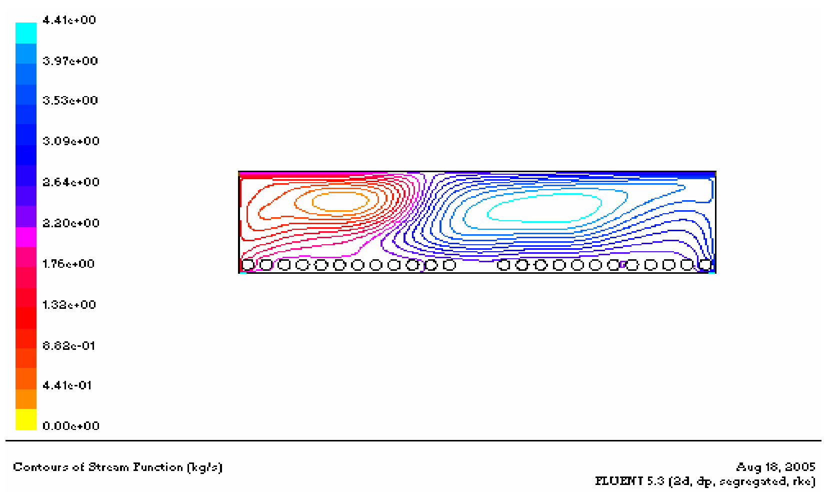


Figure 6.1.3.8: Streamlines for two inlets at both side wall and two outlets at an open space below the floor; Vin= 5m/s under daylight situation.

For layout 1, as can be seen in figure's 6.1.3.9 and 6.1.3.10, the temperature varied from 30.03°C to 29.98°C. The reason for that seems to be due to little mixing of the entering air has with the original air in the left hand side of the room. The fresh air enters through the side wall moving symmetrically as a jet and direct to the exit, bypassing the air at the pigs' level in left hand side. Therefore, the velocity distribution at right hand side is much higher which 2.25 ms^{-1} is than the left hand side which approximately to 0 ms^{-1}. This situation happened because fresh air entered in from left wall was mixed with room air closely to the ceiling become warm air. Theoretical, warm air always on top level compare with cool air therefore, the velocity did not distribute much at the left hand side of the housing. On the right hand side, velocity distributions higher because the incoming pressure from opposite of velocity direction was larger then the velocity direction give. Therefore, velocity re-circulate mixed with the room air then exhaust out by fan.

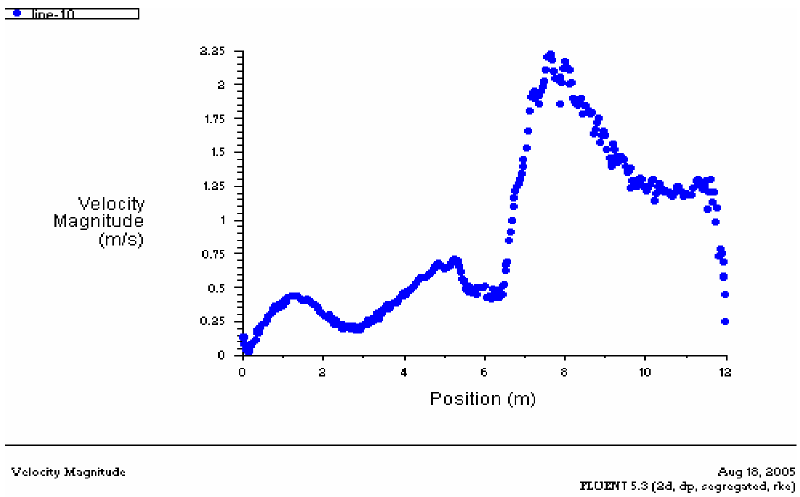


Figure 6.1.3.9: Velocities distribution at the pigs' level for layout 1;Vin=5m/s under daylight situation.

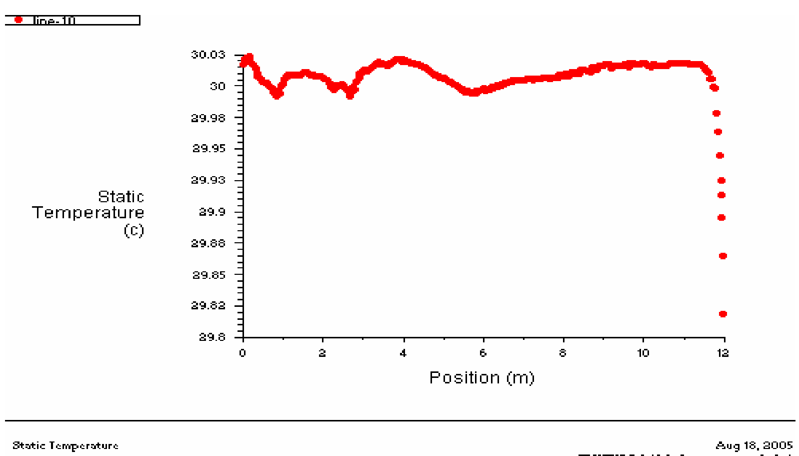


Figure 6.1.3.10: Temperature distribution at the pigs' level for layout 1; Vin=5m/s under daylight situation.

Layout 2 gave a temperature variation of 0.055°C with a maximum temperature of 30.04°C. For one outlet (layout 1) and two outlets (layout 2) cases the velocities in the middle of the room were close to uniform, being around 2 m/s and 1.7 m/s, respectively.

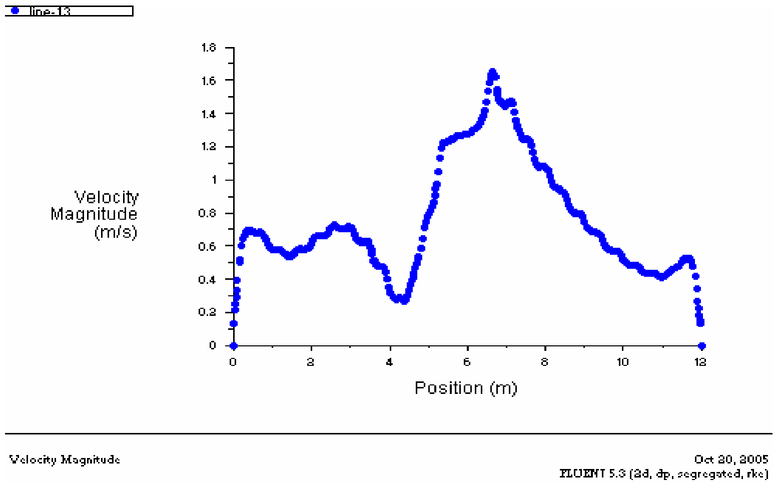


Figure 6.1.3.11: Velocities distribution at the pigs' level for layout 2; Vin=5m/s under daylight situation.

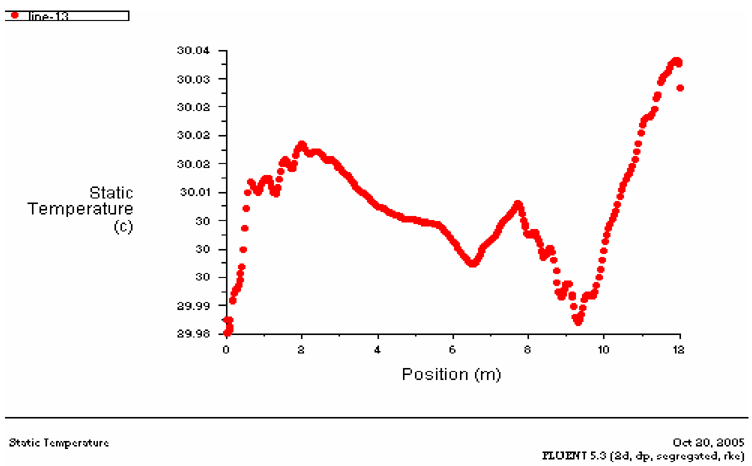


Figure 6.1.3.12: Temperature distribution at the pigs' level for layout 2; Vin=5m/s under daylight situation.

On the other hand, for layout 3 the temperature variations were found to be 0.02°C with a maximum temperature of 30.04°C and the velocities was approximately zero at the middle of the housing this can see in figure 6.1.3.13. Therefore, the room may not have 'good' velocity distribution.

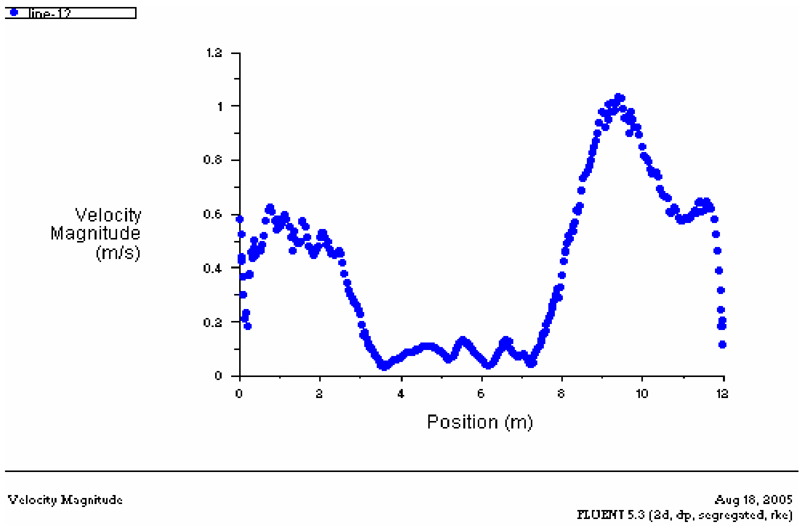


Figure 6.1.3.13: Velocities distribution at the pigs' level for layout 3; Vin=5m/s under daylight situation.

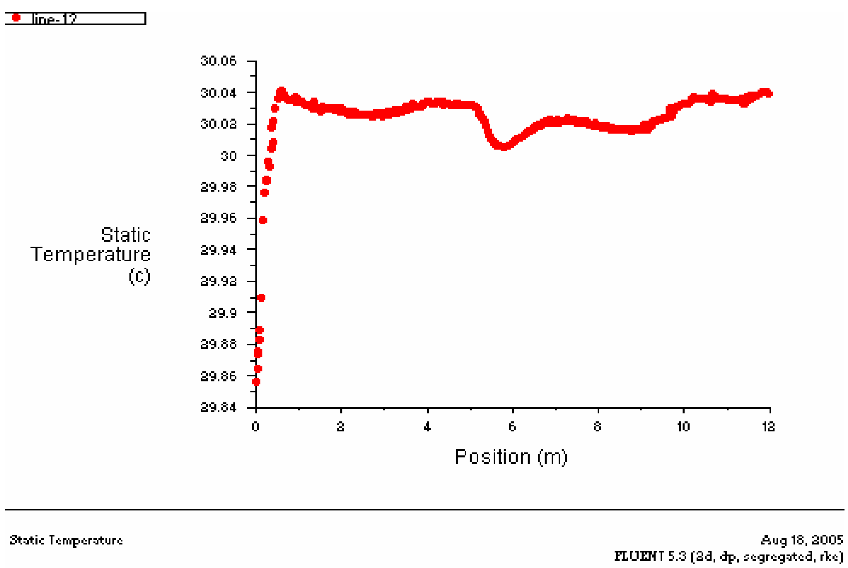


Figure 6.1.3.14: Temperature distribution at the pigs' level for layout 3; Vin=5m/s under daylight situation.

For layout 4, the temperature variation were found to be 0.04°C with a maximum temperature of 30.02°C and velocities were almost similar at each half of housing.

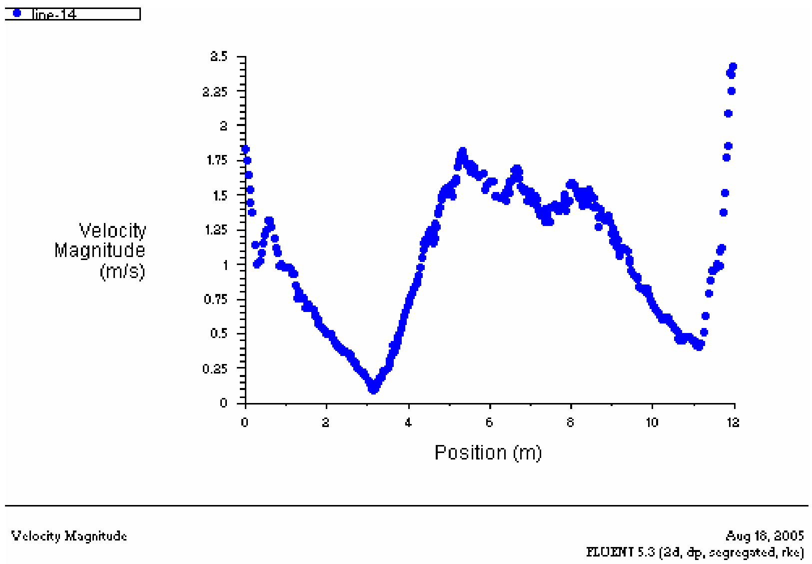


Figure 6.1.3.15: Velocities distribution at the pigs' level for layout 4; Vin=5m/s under daylight situation.

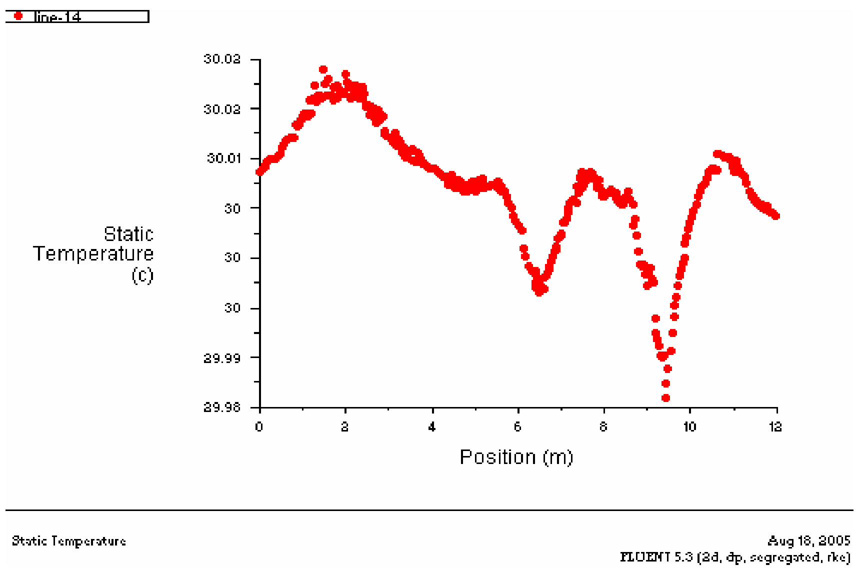


Figure 6.1.3.16: Temperature distribution at the pigs' level for layout 4; Vin=5m/s under daylight situation.

Figures 6.1.3.17 to 6.1.3.24 present the velocity and temperature distributions at the pigs level for night situations at ambient temperature, 26 °C and at Vin=5m/s. The results show that at night, where low air flow is used in ventilation, variations of temperature are small. This is expected because in Malaysia the change of ambient temperature between daylight (30 °C) and night (26°C) is small. For layout 1, the temperature variation is 0.025 °C with a maximum temperature of 26.05 °C.

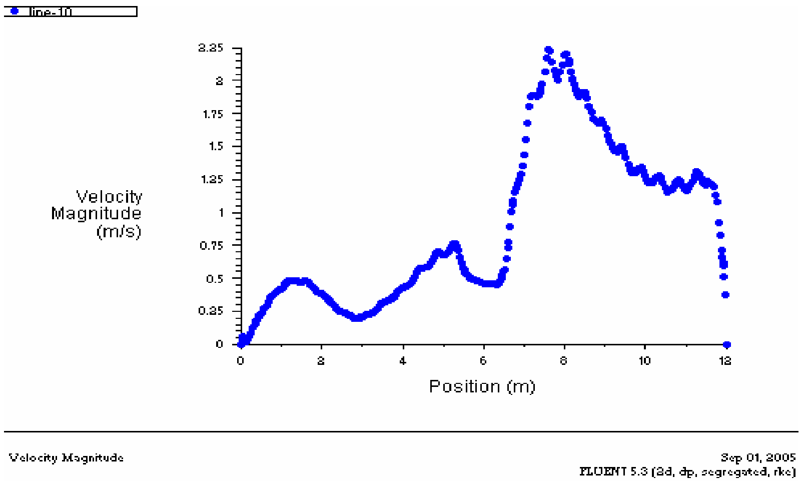


Figure 6.1.3.17: Velocities distribution at the pigs' level for layout 1; Vin=5 m/s under night situation.

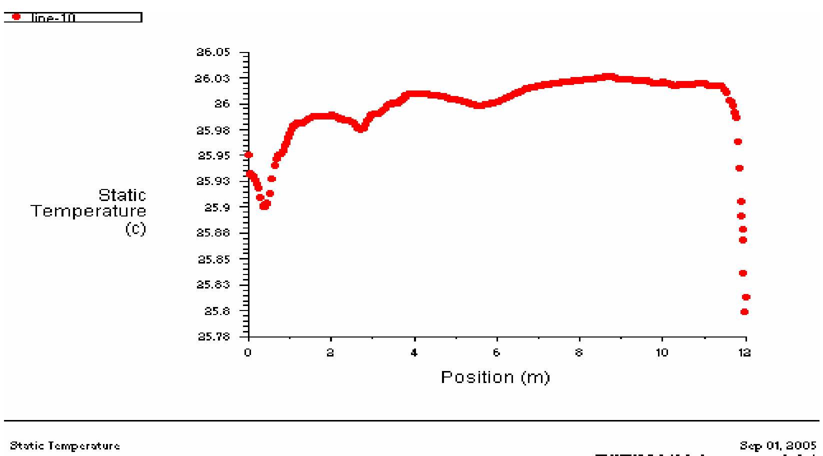


Figure 6.1.3.18: Temperature distribution at the pigs' level for layout 1; Vin=5 m/s under night situation.

For layout 2 the variation of temperature is 0.01 °C with a maximum temperature of 26.01°C. The temperature distribution for layout 2 in daylight was different from the distribution at night because the temperature difference between the outside temperature and the pig temperature is larger, thus suggesting a larger heat transfer rate.

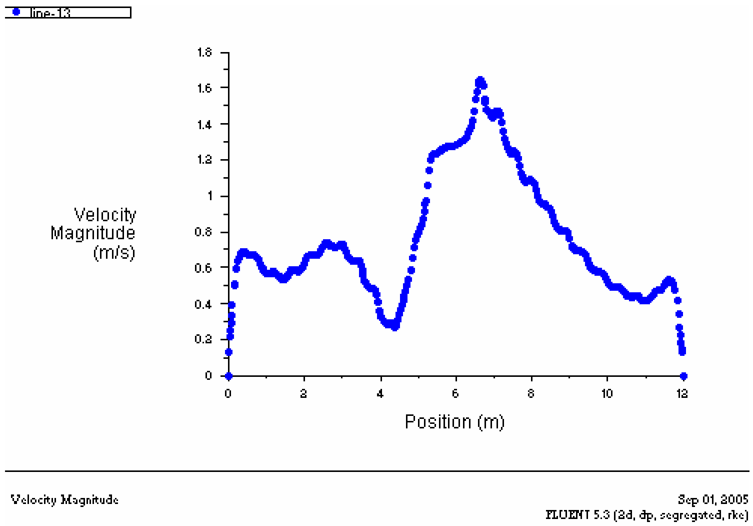


Figure 6.1.3.19: Velocities distribution at the pigs' level for layout 2; Vin=5 m/s under night situation.

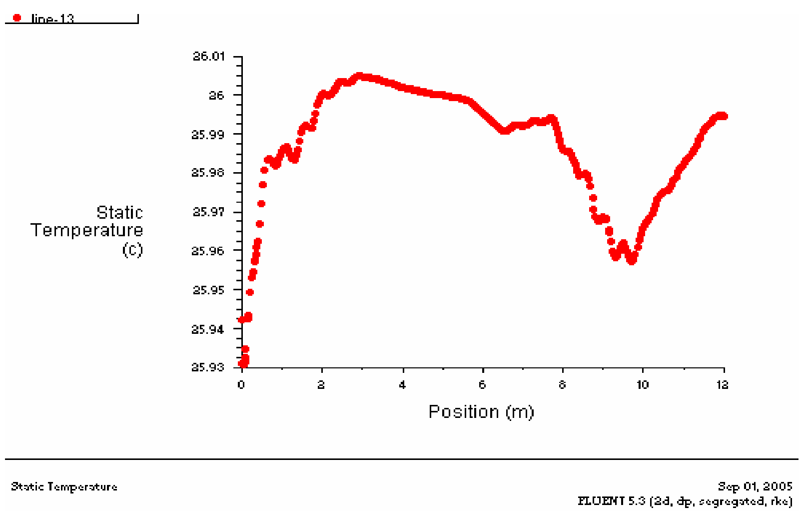


Figure 6.1.3.20: Temperature distribution at the pigs' level for layout 2; Vin=5 m/s under night situation.

However, for layout 3, velocities at the pigs' level are still very low, the temperature variation is approximately 0.05°C with a maximum temperature of 26.02°C

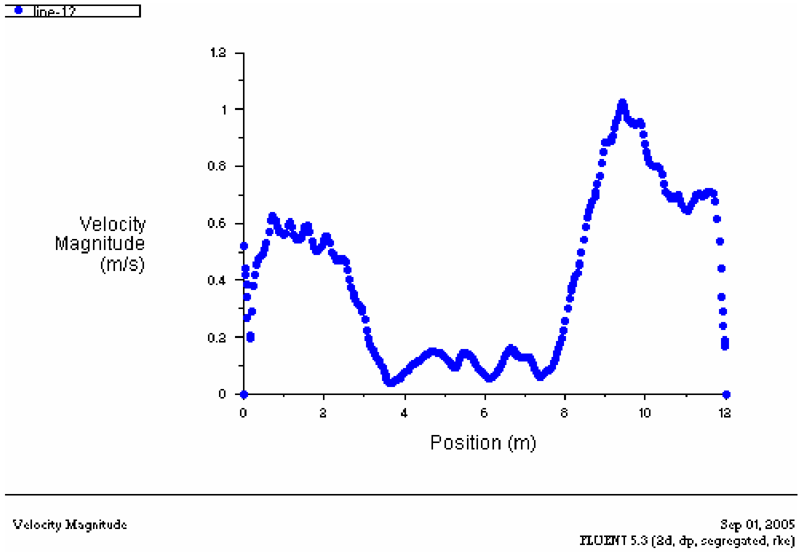


Figure 6.1.3.21: Velocities distribution at the pigs' level for layout 3; Vin=5 m/s under night situation.

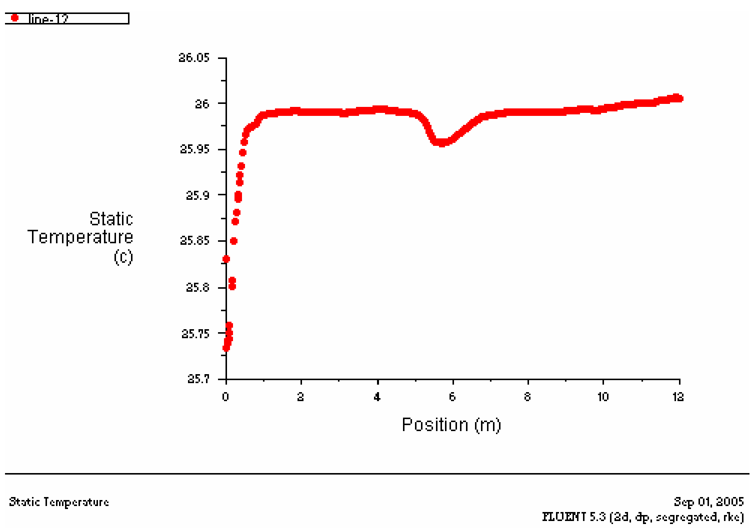


Figure 6.1.3.22: Temperature distribution at the pigs' level for layout 3; Vin=5 m/s under night situation.

For layout 4 there is a temperature variation of 0.055°C with a maximum temperature of 26.01 °C predicted.

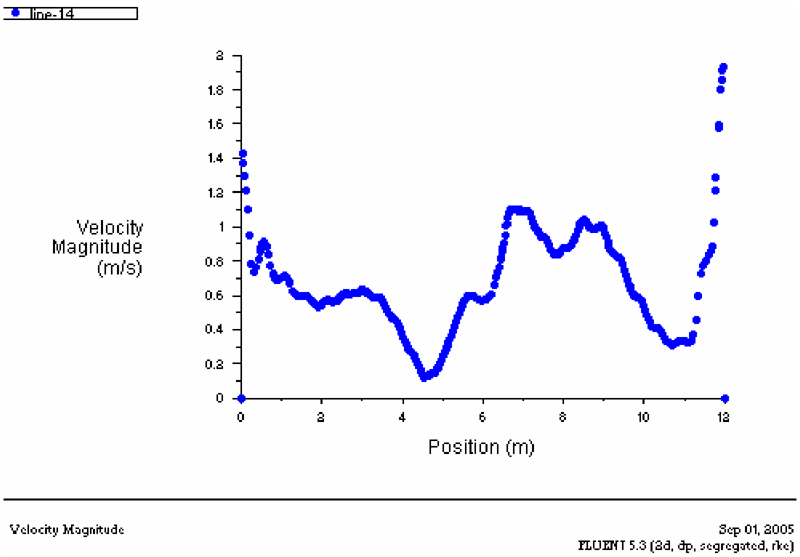


Figure 6.1.3.23: Velocities distribution at the pigs' level for layout 4; Vin=5 m/s under night situation

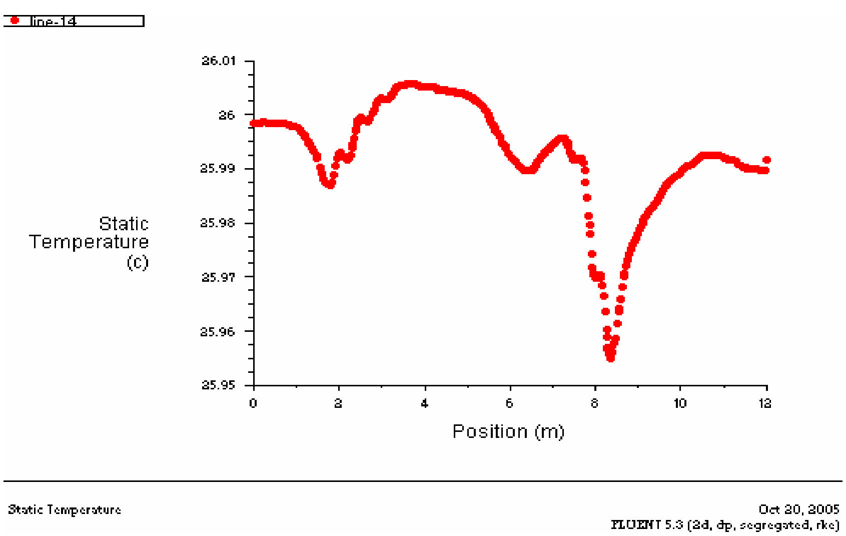


Figure 6.1.3.24: Temperature distribution at the pigs' level for layout 4; Vin=5 m/s under night situation.

The graphs shown below were the combination temperature for all of the layouts. In layout 4, shows a bit lower temperature compare the others layout this is because the outlets at open air space below the floor may allow the pigs give off the heat by convection heat transfer to outside building. Overall results present that under daylight situation average maximum temperature were at the constant value of 30.01°C. In this situation, pigs feel heat stress and water sprayers system has to be installed. Spraying water on the pigs' bodies will have cooling effect, since heat is removed from the pigs' bodies as water evaporates.

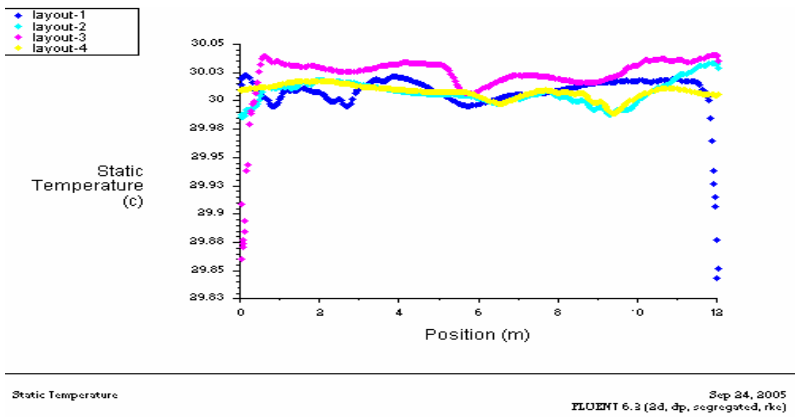


Figure 6.1.3.25: Temperature distribution at the pigs' level for all layouts under night situation.

While, under night situation, all of the layouts shown, the results maximum temperature are only 26.2°C which is within the range of the optimum range of temperature of pigs. Therefore, pigs will feel comfortable at night.

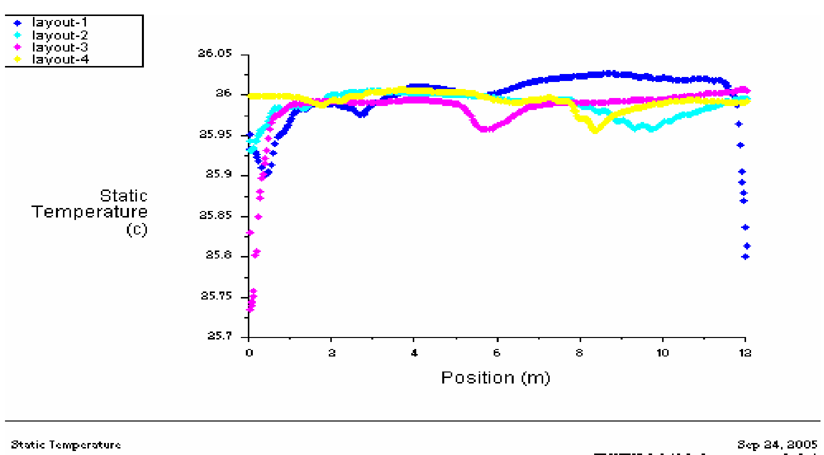


Figure 6.1.3.26: Temperature distribution at the pigs' levels for all layouts under night situation.

The air in the pig house includes gaseous contaminants, heat, moisture and feces need to be quickly diluted. Accumulation of these unwanted compounds will provide negative impact to the comfort of pigs. Therefore, ventilation needs to be designed properly in order to provide pig housing with environment of good airflow pattern. Layout 1 and 4 seems to be the best among the layouts because clean air completely moved through the housing air space to dilute and remove the contaminants and replenish oxygen levels. Layout 3 was not recommended because improper inlet location does not allow for the recommended air exchange, therefore too much re-circulated air exist in the room. On the other hand, layout 2 was also not recommended as the additional outlet did not show much improvement of the velocity magnitude and static temperature distributions at the pigs' level. The additional outlet increases the capital and operating cost.

At night, activity of the pigs will be very much less compared with daytime. Most of the pigs will either be resting or sleeping and less physical activity from pigs. Therefore the static temperature distributions at pigs' levels were within the thermal comfort criteria for pigs. From the simulations, it was found that pigs will be in thermal comfortable zone at night; while during daylight it may be a problem for pigs to be in the thermal comfortable zones because of the average ambient temperature in daylight for Malaysia is 30 °C, and the CFD simulations showed that the static temperature in all four layouts investigated are higher than the optimum comfort temperature. If the heat given out by the pigs is not removed, the pigs may die because of heat stress. To overcome this problem, using water sprayer during daytime is essential for pig housing in Malaysia.

6.1.4 Part C: Sprayer Cooling

Typical Malaysia hot weather (above 30°C) can reduce pig fertility, appetite and feed utilization efficiency. Spray cooling can alleviate the effect of high temperatures.

From the analysis in part B, layout 1 was chosen for this improvement (using sprayer cooling). Figure, 6.1.4.1, presents the installed water sprayer system in FLUENT. A spray cooling system is installed at the ceiling of the room which produces water at temperature 25°C, and flow rate 0.01m/s. However, time needed depends on flow rate; therefore in figure 6.1.4.3 to 6.1.4.6 present when flow rate is small the time of spraying should be longer to achieve the thermal comfort level.

When all sprayers are operating, the water supply system must be able to deliver sufficient water at the design pressure, and satisfy all other farmstead water needs (drinking water, flush water, etc) which occurs simultaneously. When the water supply flow rate is limited, consider a reservoir for water accumulation during off periods. The controller switches the system on and off with a solenoid valve automatically, either by setting a cycle run-time or between cycles on a controller and with a thermostat. CFD can help determine the best location for such thermostat.

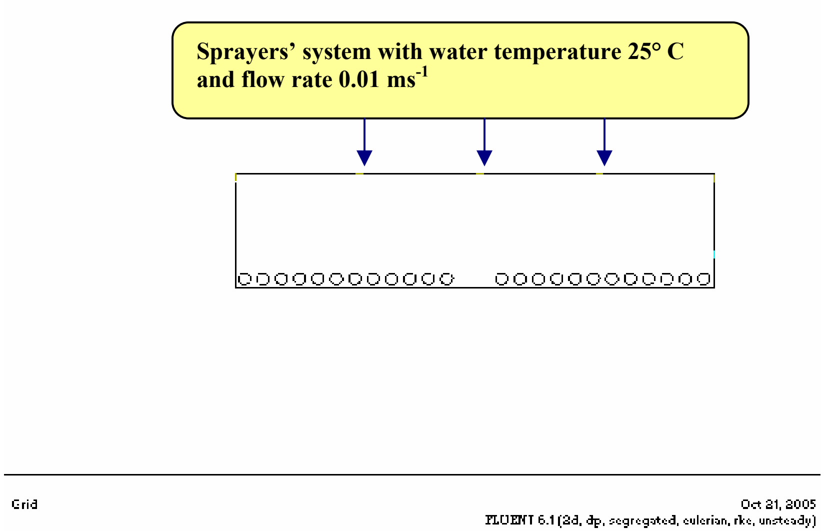


Figure 6.1.4.1 Simulation model of water sprayers' system installed.

Figure 6.1.4.2 show the contour temperature when water sprayers system is not being applied in the model after 30 seconds and the temperature stated approximately 30.2°C.

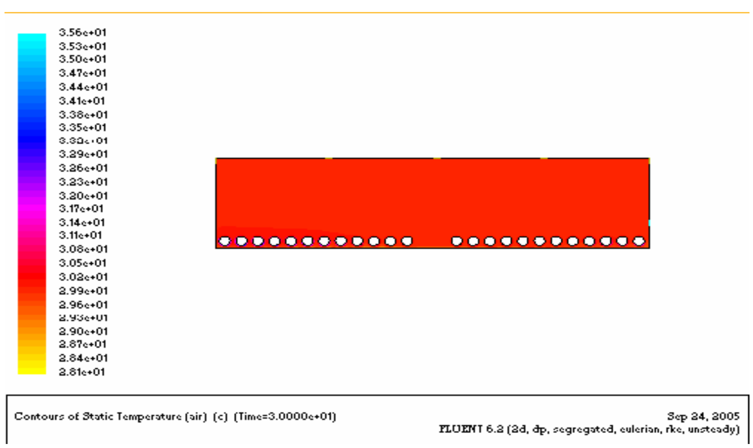


Figure 6.1.4.2: Temperature distribution at the pigs' level before sprayers' system operates (30sec).

and figure 6.1.4.3 and 6.1.4.4 show the temperature distribution at the pigs level after operating the sprayer system for 30 seconds, temperature was found to drop to approximately 26.4°C .

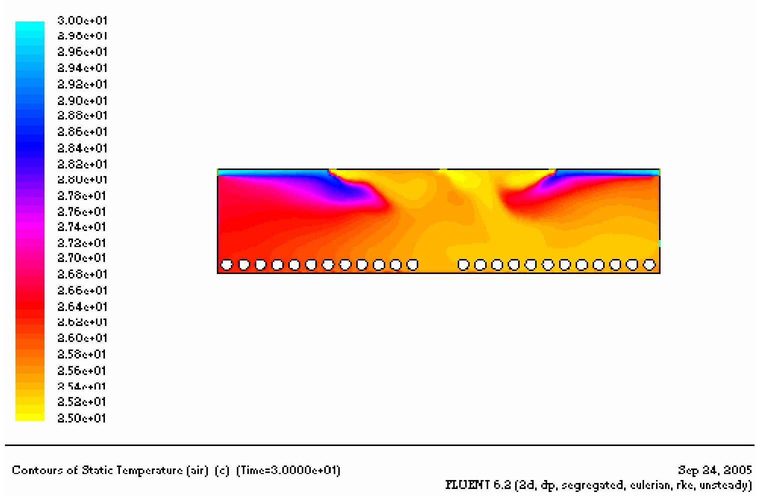


Figure 6.1.4.3: Temperature distribution at the pigs' level after sprayers' system operates (30sec), flow rate 0.01m/s

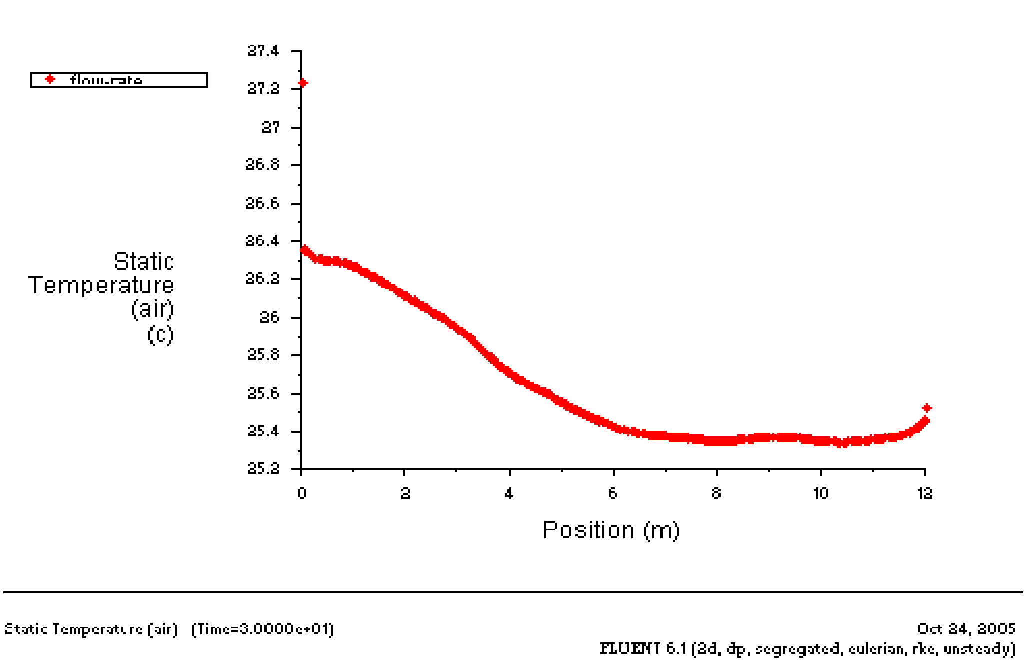


Figure 6.1.4.4: Plotted graph of temperature distribution at the pigs' level after sprayers' system operates (30sec), flow rate 0.01 m/s

On the other hand, figure 6.1.4.5 and 6.1.4.6 show the low flow rate of the temperature distribution at the pigs level after operating the sprayer system for 60 seconds, temperature was found to drop to approximately 26.75 °C and it was doubled up the time to achieve thermal comfort level compare with flow rate 0.01m/s.

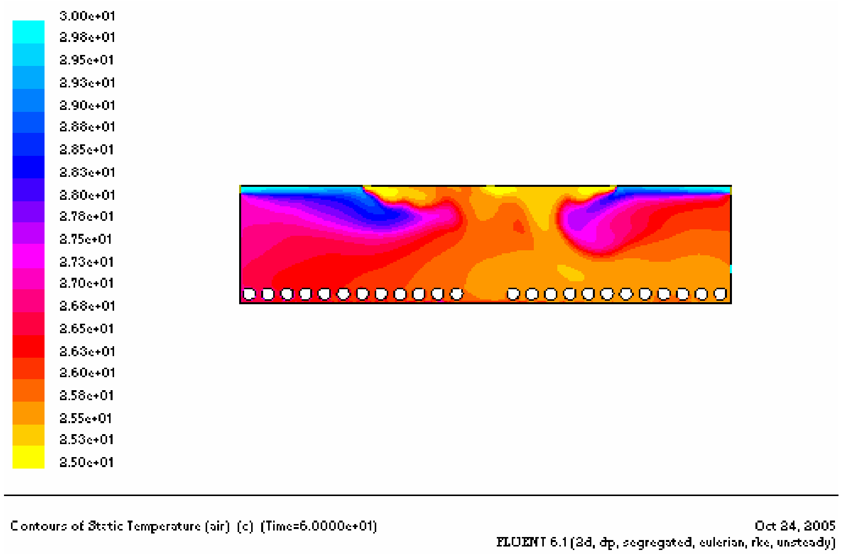


Figure 6.1.4.5: Temperature distribution at the pigs' level after sprayers' system operates (60sec), flow rate 0.005m/s

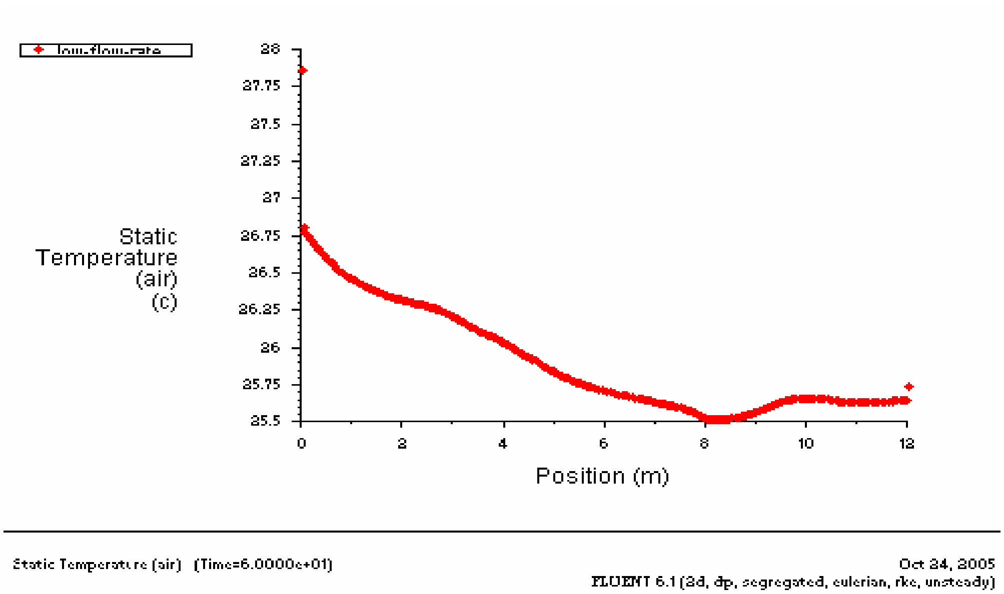


Figure 6.1.4.6: Plotted graph of temperature distribution at the pigs' level after sprayers' system operates (60sec), flow rate 0.005 m/s

Figure 6.1.4.7 show the combination of the flow rate in plotted graph of temperature distribution at the pigs' level after sprayer's system operates in 30 seconds. It was the expectation; time depends on the flow rate. From the analysis, in order to let pigs feel comfortable (faster) therefore flow rate of 0.01 m/s is considered.

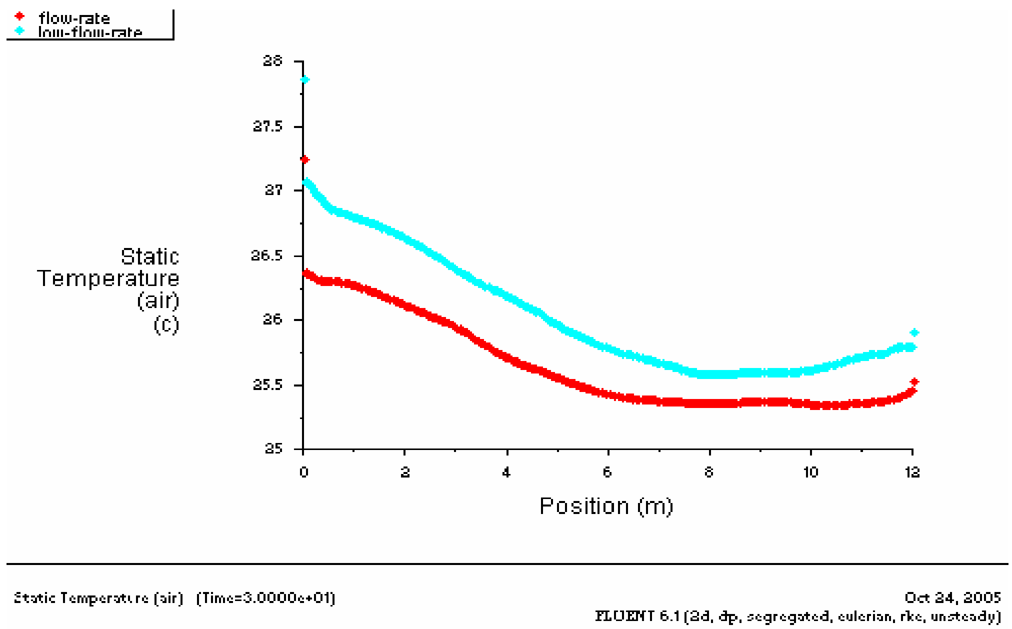
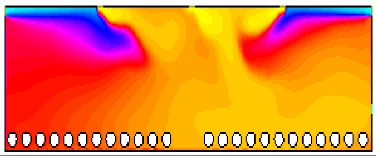
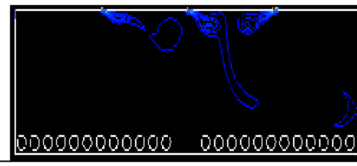
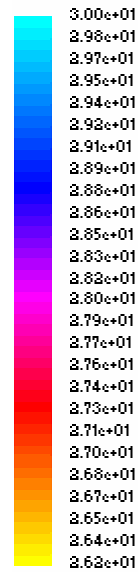
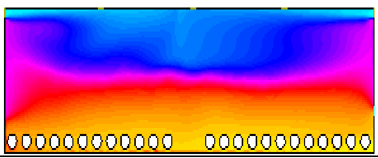
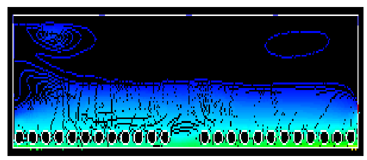
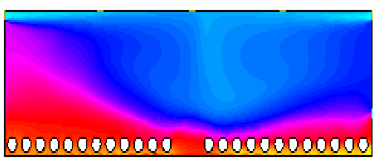
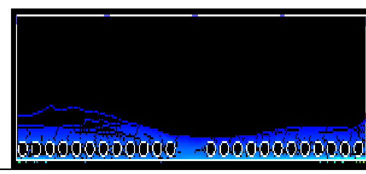
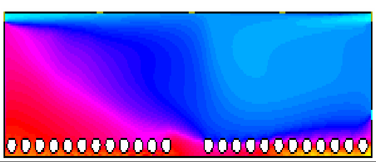
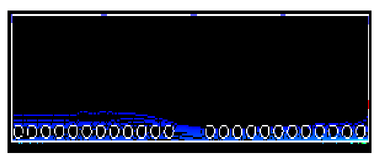
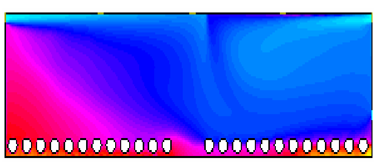
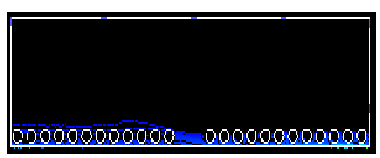
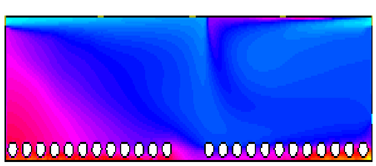
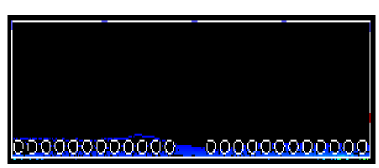


Figure 6.1.4.7: Plotted graph of temperature distribution at the pigs' level after sprayers' system operates (30sec) with different flow rate.

Table 6.1.4.1 presents the temperature changes and the volume fraction of simulation model for on off period of the sprayers' system until 180 seconds.

Table 6.1.4.1 Temperature distribution at pig's level for every 30 seconds

Sprayer operation	**Simulation model of temperature changes**	**Simulation model of volume fraction**	
ON till 30 seconds			Temperature °C 
Off till 31 to 60 seconds			
Off till 61 to 90 seconds			
Off till 91 to 120 seconds			
Off till 121 to 150 seconds			
Off till 151 to 180 seconds			

From the simulations, the prediction of humidity level in the pig housing may be tolerable. However, experimental set up have to be carried out to validate the humidity level is tolerable. Figure 6.1.4.4 presents the temperature distribution at pig's level as a function of time for daylight situations at ambient temperature, 30°C and at Vin, 5m/s after water sprayer cooling system was operated for 30 seconds. The result showed that there was a decrease in temperature at pigs' level because cooling occurs when body heat evaporates the water from pigs. The thermostat activates the sprayers system when the air temperature exceeds a given set point (usually 29°C to 30°C) and turns the system off (after 30 seconds). With the installation of the thermostat, the pigs will be comfortable under daylight and night situation.

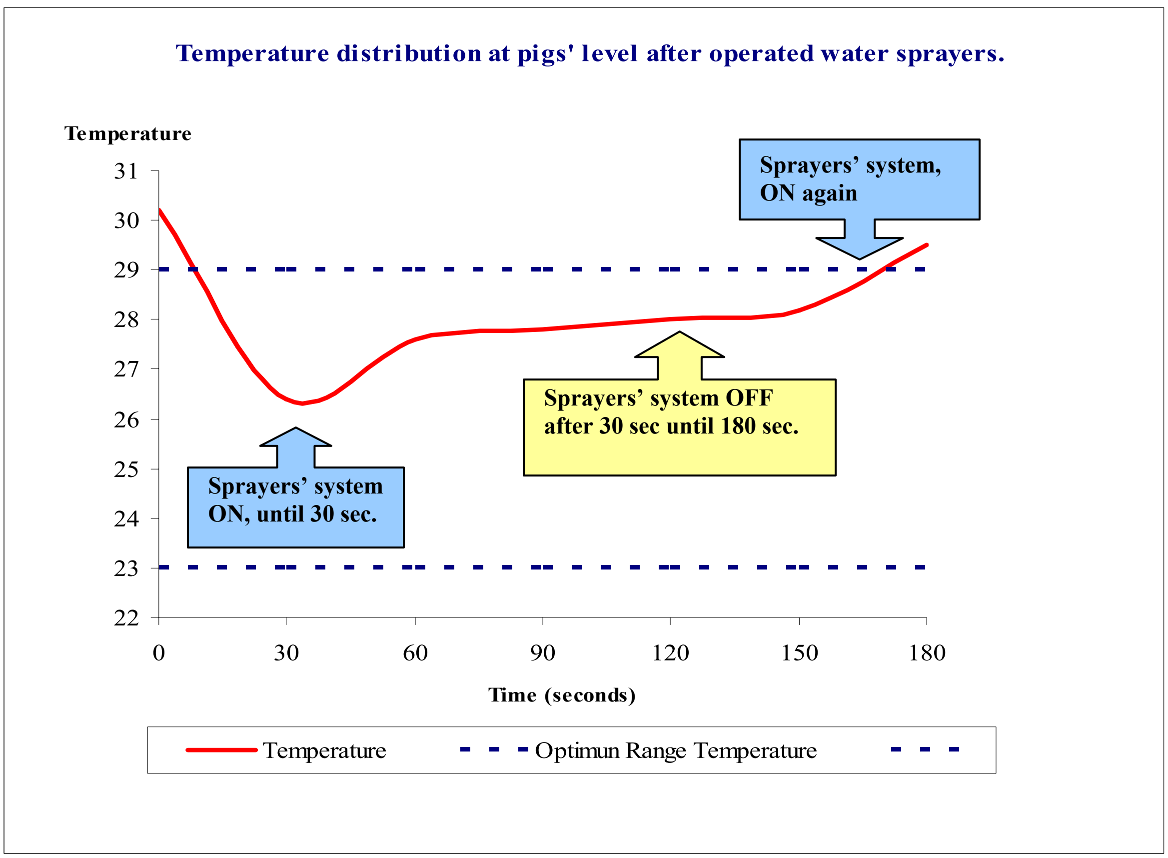


Figure 6.1.4.8: Temperature distribution at the pigs' level versus time

CHAPTER SEVEN

CONCLUSIONS

7.1 Achievement of the objectives

Proper inlet arrangement is critical to ensure that the incoming air has enough momentum to throw the fresh air across the ceiling to mix with the warm inside air. The momentum depends largely on the air velocity. On the other hand, improper inlet management results in either not enough air coming into the room, or the airflow being directed downward due to its low momentum.

The two turbulent models employed in this study demonstrated rather obvious differences. The realizable k-ε model satisfies certain mathematical constraints on the normal stresses, and is consistent with the physics of turbulent flows. In contrast, standard k-ε model did not fulfill the mathematical constraints, and therefore is expected to be less accurate than the realizable k-ε model.

Velocities and temperatures at the pigs' level for mechanical ventilated pig housing were predicted for different arrangements under daylight and night situation. For the geometry chosen, layout 1 and layout 4 appears to facilitate better mixing air inside the pig housing and to offer air distribution within the thermal comfort zone for grower and finisher. However the model results suggest that for daylight situation, water sprayer cooling has to be used to bring temperatures to within the pigs' thermal comfort zones.

The simulation tools, CFD proved to be helpful in analyzing the airflow within the pig housing and can be used as a valuable design tool. It helps in predicting the performance of a particular design and offers suggestions to improve the existing designs.

7.2 Future study

The simulation results presented in the project showed that the presence of pigs affected the airflow pattern. It would be more useful to predict the airflow pattern after including all solid objects found in pig housing. For example, the objects such as feeders and mechanical equipment may alter the air flow in the room. Besides, the effects of heat generated by the pigs on the air flow pattern were approximated by assuming a constant heat flux at the floor surface. It remains to investigate the combined effect of the physical obstruction and the heat production of the pigs in greater detail, using a more realistic simulation of the geometry of the problem. A three-dimensional model should be investigated in order to improve the air quality in the domain and enhance the heat removal efficiency in pig housing.

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APPENDICES

- **Appendix A: Project Specification**
- **Appendix B: Dimensionless groups**
- **Appendix C: Interpretation**

Appendix A: Project specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project

PROJECT SPECIFICIATION

FOR:	**Alan CHAN Teck Wai**
TOPIC:	COMPUTATIONAL FLUID DYNAMICS (CFD) INVESTIGATION FOR IMPROVING PIG'S HOUSING DESIGN. (REF NO: 05-123)
SUPERVISOR:	Ruth Mossad
ASSOCIATE SUPERVISOR:	Dr. Thomas Choong Shean Yaw (Malaysia)
SPONSORSHIP:	Faculty of Engineering & Surveying, USQ
PROJECT AIM:	The project seeks to investigate the air flow in the pig housing, define the effect of ventilation system design on the airflow pattern in a pig housing and their implications for how the size of an air inlets bring in fresh air to supply animal needs.

PROGRAMME: **Issue A, 21st March 2005**

1. Research the background information relating to pig housing ventilation such as types, thermal comfort level of pigs at different ages, heat transfer
2. Research the effects that different inlets design; define major factors that affect the increasing pig's production efficiency.
3. Conduct a literature search for the topic.
4. Modeling the mechanical ventilated pig housing using software "GAMBIT version 2.1" and investigate how important of the system components (e.g. fans, openings, control) affect the air distribution or mixing in pig housing.
5. Use software "FLUENT" to model two-dimensional model and investigate the air flow patterns in the pig housing for a variety of different location of variable inlet velocities.
6. Present results, conclusion and recommendation for how to improve the pig housing design.

AGREED: ________________, (Student) ________________,(Supervisor)

Alan CHAN Teck Wai Ruth Mossad

_____/_____/______ _____/_____/______

_______________, (Assoc. Supervisor)

Dr.Thomas Choong Shean Yaw

_____/_____/_____

Appendix B: Dimensionless groups

Q net=f(k_a,V, q,…L,W,H, X_w, …)

Parameter	Symbol	S.I units	Fundamental
Thermal conductivity (air)	k_a	$Wm^{-1}K^{-1}$	$MLT^{-3}\theta^{-1}$
Thermal capacity	Q	W	ML^2T^{-3}
Time	t	s	T
Spec. heat capacity (air)	C_a	$Jkg^{-1}K^{-1}$	$L^2T^{-2}\theta^{-1}$
Density (air)	ρ_a	kgm^{-3}	ML^{-3}
Internal dimensions, Length	L	m	L
Internal dimensions, Width	W	m	L
Internal dimensions, Height	H	m	L
Hydraulic diameter	D_h	m	L
Materials thickness of wall	X_w	m	L
Materials thickness of ceiling	X_c	m	L
Materials thickness of floor	X_f	m	L
Velocity	V	ms^{-1}	LT^{-1}
Heat generation	q	W/m3	$ML^{-1}T^{-2}$
Dynamics viscosity	μ	Ns/m^2	$ML^{-1}T^{-1}$

Independent variables, (k_a, V, ρ_a, D_h)

Therefore the dimensional groups as below:

1. *pi1=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d (Q)$

$$(MLT^{-3}\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (ML^2T^{-3})$$

$a=0, b=-3, c=-1, d=-2$

$$=\frac{Q}{\rho_a V^3 D_h^{\ 2}}$$

2. *pi2=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d (t)$

$(MLT^{-3}\,\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (T)$

a=0, b= 1 c= 0 d=-1

$= \frac{Vt}{Dh}$

3. *pi3=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d\, Ca$

$(MLT^{-3}\,\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (L^2T^{-2}\,\Theta^{-1})$

a=-1, b=1 c= 1 d=1

$= \frac{V\rho_a C_a D_h}{k_a}$

4. *pi4=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d (W)$

$(MLT^{-3}\,\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (L)$

a=0, b=0, c= 0 d=-1

$=W (D_h)^{-1}$

5. *pi5=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d (L)$

$(MLT^{-3}\,\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (L)$

a=0, b=0, c= 0 d=-1

$=L (D_h)^{-1}$

6. *pi6=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d (L)$

$(MLT^{-3}\,\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (L)$

a=0, b=0, c= 0 d=-1

$=H (D_h)^{-1}$

7. *pi7=* $(k_a)^a (v)^b (\rho_a)^c (D_h)^d (X_w)$

$(MLT^{-3}\,\theta^{-1})^a (LT^{-1})^b (ML^{-3})^c (L)^d (L)$

a=0, b=0, c= 0 d=-1

$= X_w\ (D_h)^{-1}$

8. *pi8=* $(k_a)^a\ (v)^b\ (\rho_a)^c\ (D_h)^d\ (Xc)$

$(MLT^{-3}\ \theta^{-1})^a\ (LT^{-1})^b\ (ML^{-3})^c\ (L)^d\ (L)$

a=0, b=0, c= 0 d=-1

$= X_c\ (D_h)^{-1}$

9. *pi9=* $(k_a)^a\ (v)^b\ (\rho_a)^c\ (D_h)^d\ (Xw)$

$(MLT^{-3}\ \theta^{-1})^a\ (LT^{-1})^b\ (ML^{-3})^c\ (L)^d\ (L)$

a=0, b=0, c= 0 d=-1

$= X_f\ (D_h)^{-1}$

10. *pi10=* $(k_a)^a\ (v)^b\ (\rho_a)^c\ (D_h)^d\ (q)$

$(ML^{-3}T^{-3}\ \theta^{-1})^a\ (LT^{-1})^b\ (ML^{-3})^c\ (L)^d\ (ML^{-1}T^{-3})$

a=0, b=-3, c= -1 d=5

$$= \frac{q}{V^2 \rho_a}$$

11. *pi11=* $(k_a)^a\ (v)^b\ (\rho_a)^c\ (D_h)^d\ (\mu)$

$(ML^{-3}T^{-3}\ \theta^{-1})^a\ (LT^{-1})^b\ (ML^{-3})^c\ (L)^d\ (ML^{-1}T^{-1})$

a=0, b=-1, c= -1 d=-1

$$= \frac{\mu}{\rho_a V D_h}$$

Final conclusion is that

$(\Pi_1 = f(\Pi_3, \Pi_4, \Pi_5, \Pi_6, \ldots))$

$(\Pi_2 = f(\Pi_3, \Pi_4, \Pi_5, \Pi_6, \ldots))$

Appendix C: Interpretation

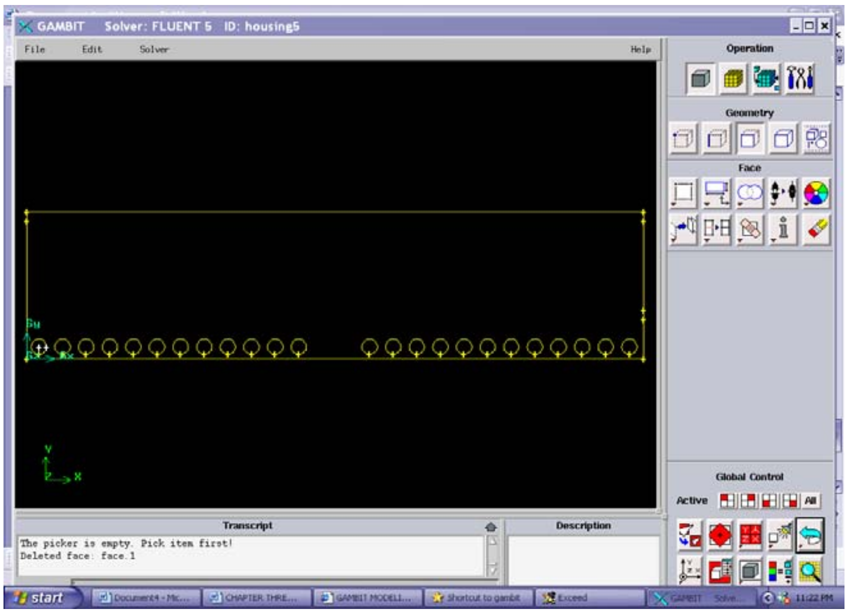
Starting GAMBIT

The model is assumed as rectangular shape in two-dimensional (2-D). Hence, the steps below have to define in order to complete the model.

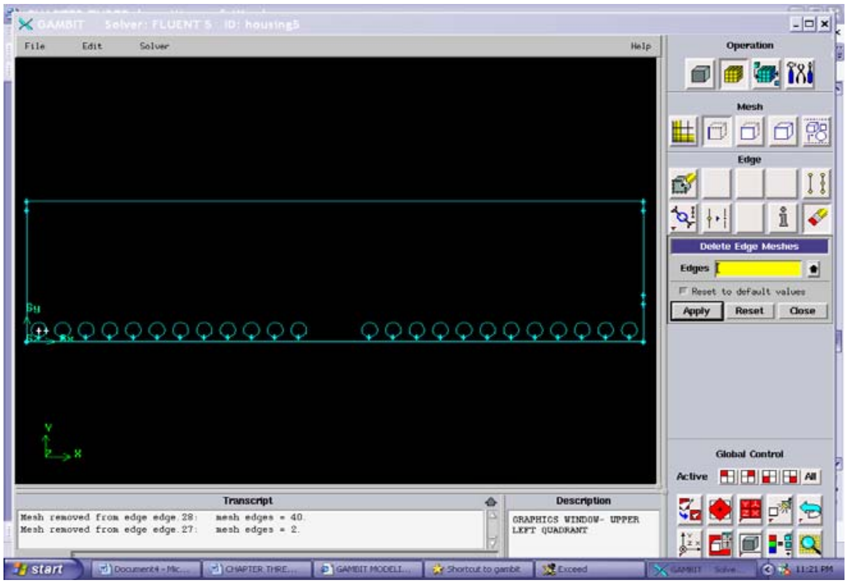
- Create vertices using a grid system

Main dimensions of the typical building section are:

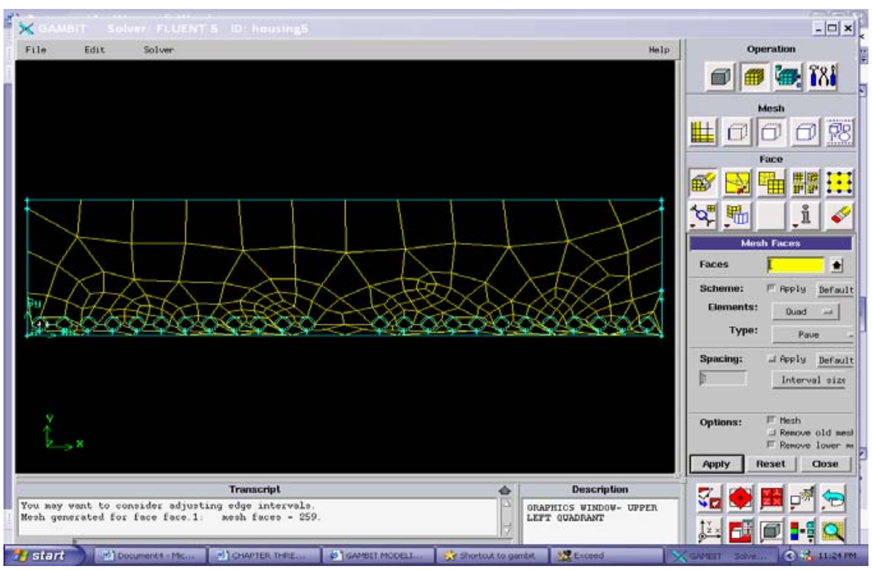
Boundary Condition	**Global**	
	x- direction	**y-direction**
Rectangular	0	0
	0	3
	12	3
	12	0
Velocity Inlet	0	2.95
	12	2.95
Exhaust Fan	12	0.8
	12	1
Pig Body	0.23	0.25
	0.38	0.25
	0.23	0.1

- For boundary condition of pig body, circles created by selecting the center of curvature and the endpoints of the arc. Then, copy the circles at each of 0.46 distances in x-direction for 24 units
- Create straight edges between vertices
- 

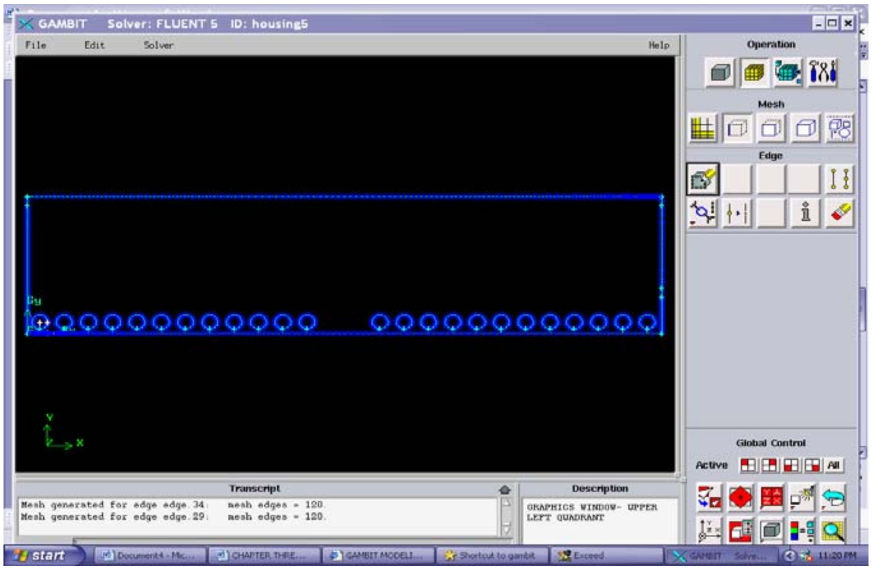
- Create faces from edges
- Then, need to take away the pigs from the domain meaning that need to subtract the circular surfaces from the original surface therefore the air flows around them.
- Finally, end up with a domain that is a rectangle with lots of holes taken away from it.



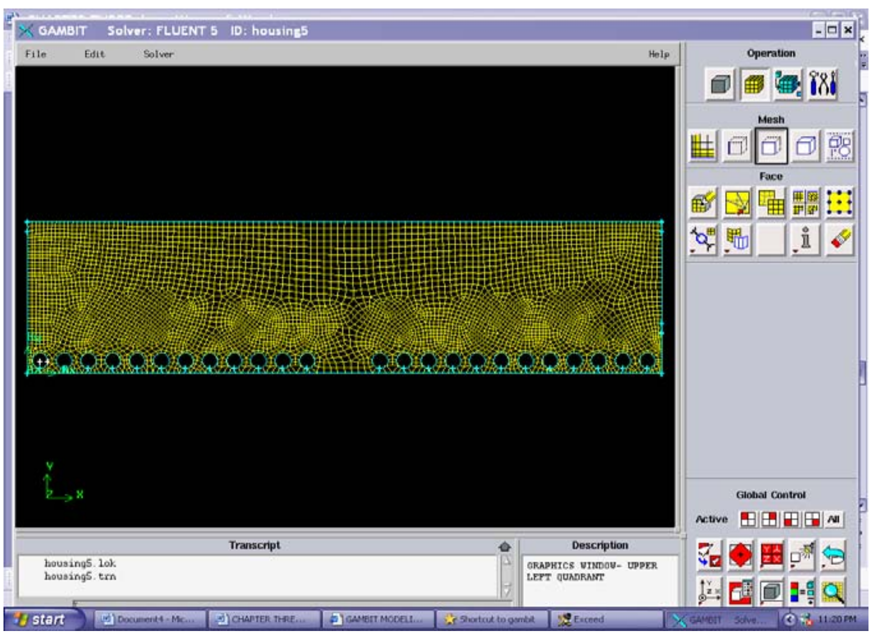
- Specify the distribution of nodes on an edge
- Create structured meshes on faces



Note: This mesh is not fine enough. Therefore, have to use the grading in the mesh



Finally, finer mesh being formed

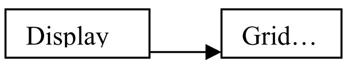


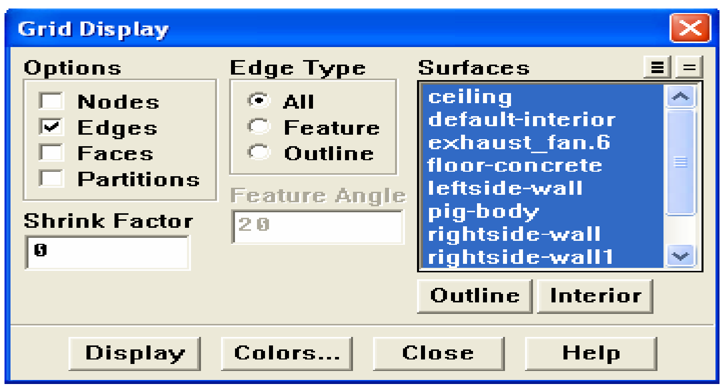
- Choose the solver FLUENT 5 and set boundary types
  - *Specify Boundary Types- i.e. wall, velocity inlets, exhaust fan*
  - *Specify Continuum Types- fluid*
- Prepare the mesh to be read into FLUENT 5.3 version.
- Export a mesh

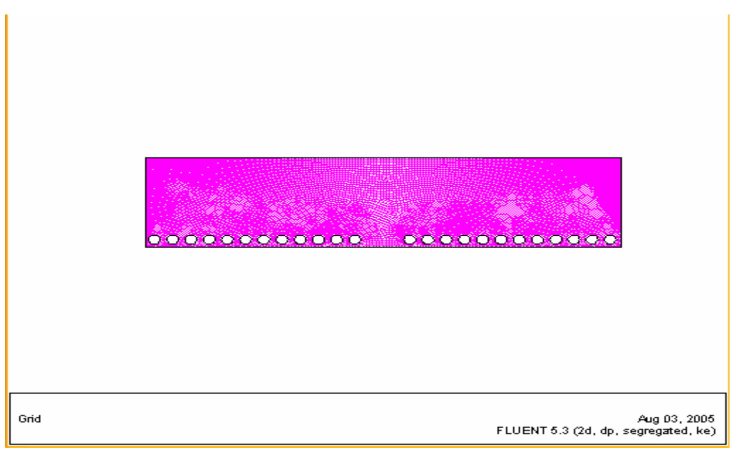
FLUENT Case (FLUENT version 5.3)

Due to the model situation, version of 2-dimenisonal double precision (2ddp) is being applied.

Step 1 Display export mesh.

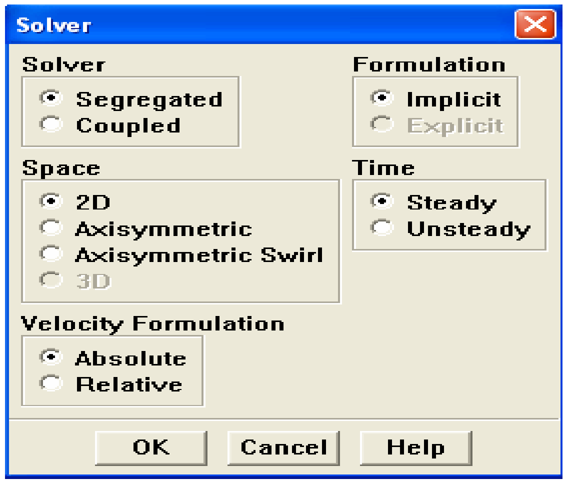






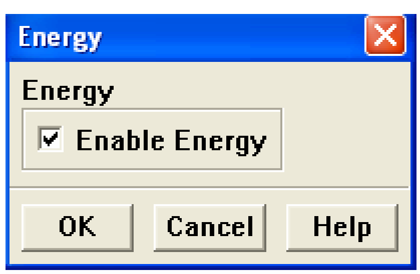
Step 2 Keep the default solver settings

Define → Model → Solver



Enable heat transfer by activating the energy.

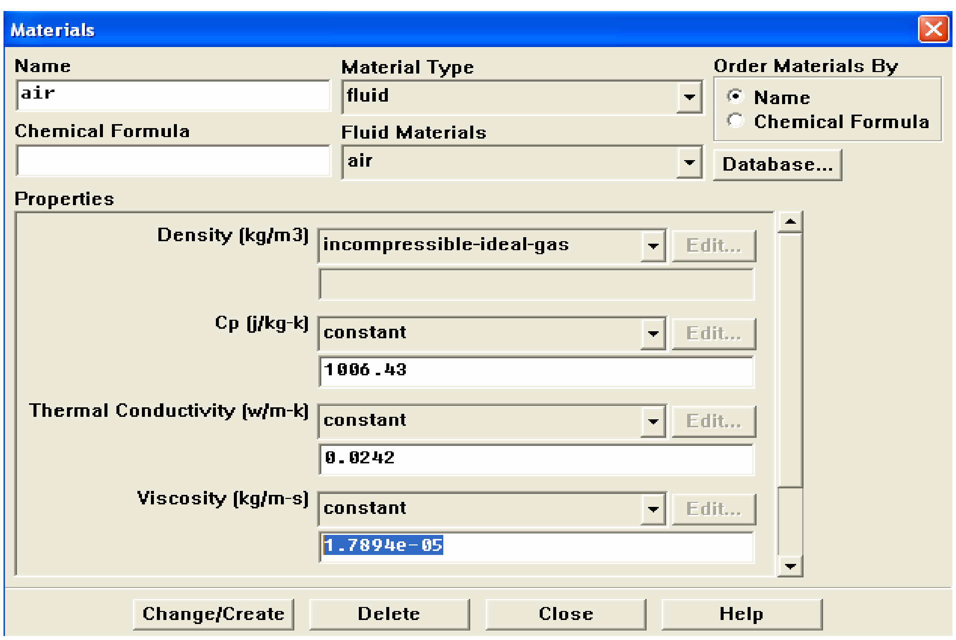
Define → Model → Energy



Step 3 Materials (Define the suitable materials properties)

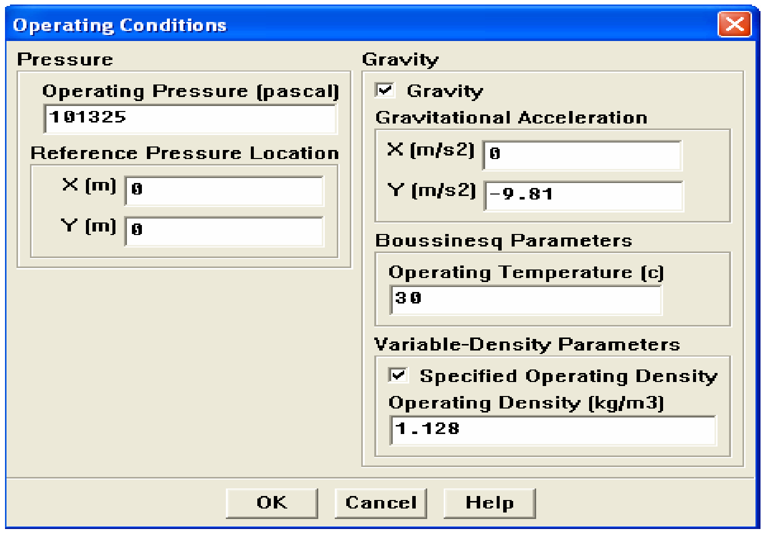
Define → Material

Material Name	**Material Type**	**Density** *kg/m^3*	**Spec. Heat Capacity** *J/kg K*	**Thermal Conductivity** *w/m^{2}k*	**Viscosity** *kg/ms*
Fresh Air	Fluid	Incompressible Ideal Gas	1006.43	0.0242	1.7894e-05
Brick common	Solid	1922	790	0.45	-
Concrete	Solid	2300	837	1.8	-
Plaster board	Solid	800	1090	0.814	-
Pig body	Solid	1200	2800	0.38	-



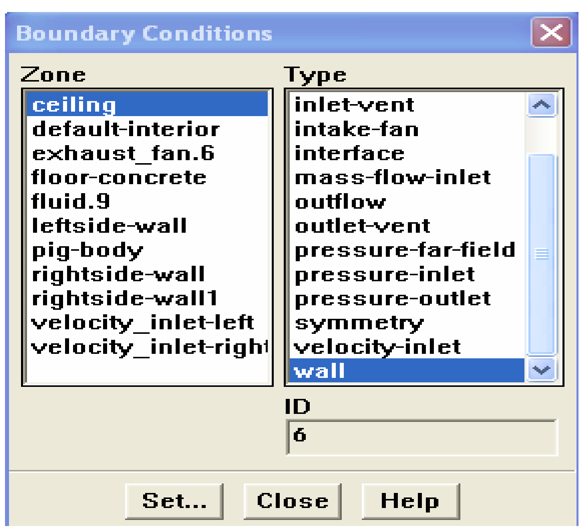
Step 4 Operating Conditions

Define → Operating Conditions



Step 5 Boundary Conditions

Define → Boundary Condition



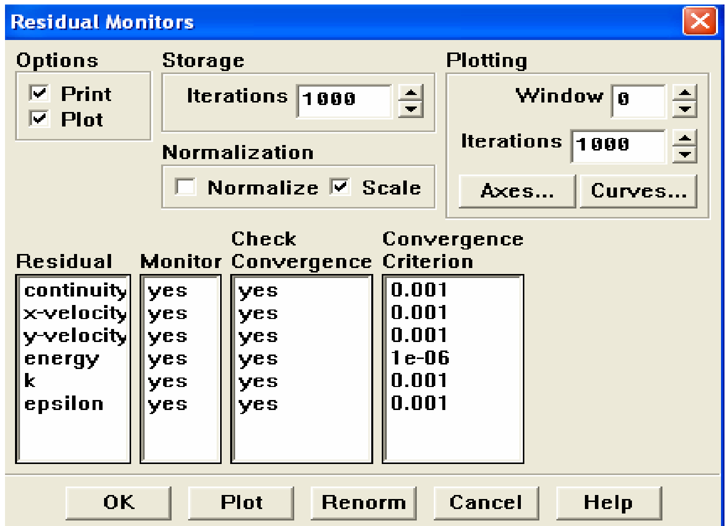
Set the boundary conditions for each zone.

Zone	**Type**	**Thermal condition**	**Free Stream Temperature,** *(°C)*	**Heat coefficient,** *w/m2k*	**Wall thickness,** *m*
Ceiling	Wall	Convection	30	2	0.1
Left side wall	Wall	Convection	30	10	0.1
Right side wall	Wall	Convection	30	5	0.1
Floor Concrete	Wall	Constant Temperature	28	-	0.1
Pig Body	Wall	Heat Flux	-	-	0.15

Zone	**Velocity magnitude** *(m/s)*	**Temp.** *(°C)*	**Turbulence specification method**	
			Turbulence intensity *(%)*	**Hydraulics Diameter,** *(m)*
Velocity inlet-left	1 – 5	30	5-10	0.05-0.4
Velocity inlet- right	1 – 5	30	5-10	0.05-0.4
Exhaust Fan	-	30	-	-

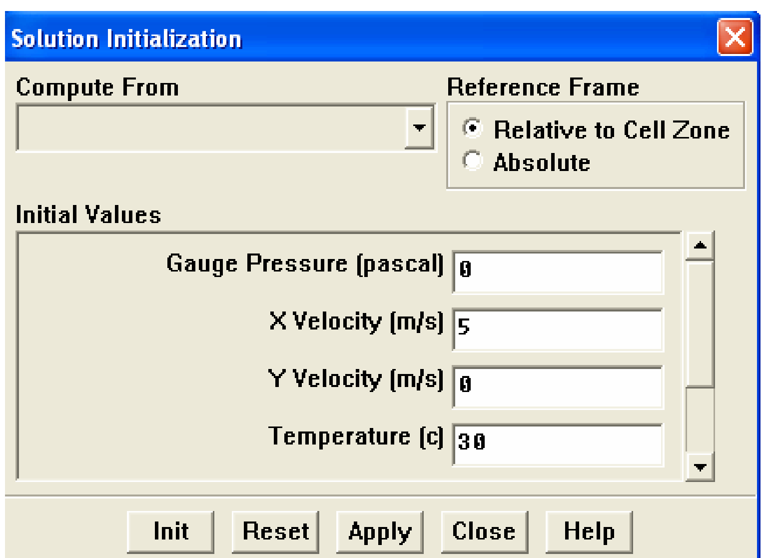
Step 6 Enabling the plotting of residuals

Solve → Monitors → Residual



Initialize the solution

Solve → Initialize → Initialize



Step 7 Display filled contour of e.g. (contour of stream function).