HEAT TRANSFER ANALYSIS OF UNDERGROUND MAJU CABLE TUNNEL

LIM SHIN FONG

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2018

HEAT TRANSFER ANALYSIS OF UNDERGROUND MAJU CABLE TUNNEL

LIM SHIN FONG

THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2018

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Lim Shin Fong

Registration/Matric No: KQK160020

Name of Degree: Master of Mechanical Engineering

Title of Project Thesis ("this Work"):

Heat Transfer Analysis of Underground Maju Cable Tunnel

Field of Study:

Mechanical Engineering- Thermodynamics Heat Transfer

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

HEAT TRANSFER ANALYSIS OF UNDERGROUND MAJU CABLE TUNNEL

ABSTRACT

This study emphasized on utilizing numerical method to determine the best ventilation method and best air flow rate for Underground Maju Cable Tunnel ventilation system. The purpose of this mechanical ventilation system is to remove the heat produce by the high tension cables in this unmanned cable tunnel and same time maintain the cable tunnel internal temperature below 40° to ensure a steady state operation condition. In this 163m long, 3m width and 2.4m height rectangular cable tunnel, there are 4 circuits of XLPE 132KV 3x1C 1000mm^2 (copper conductor) mounted in this cable tunnel and each circuit were installed in trefoil configuration. By analytical calculation, the surface temperature of the XLPE cable is approximately 56.25°C. However, surface temperature of 60°C to be applied in the simulations in order to simulate the worst case scenario. CFD software - ANSIS fluent was used for simulations and it was preset to simulate in Steady State Condition. Simulations were conducted in two types of conventional ventilation method which are Longitudinal Ventilation and Semi Transverse Ventilation. Two different air change rate, 10 Air change per hour (ACH) and 20 ACH have been applied to simulate with two different ambient temperature, 33.63°C (which is average ambient temperature in Klang Valley) and 37.00°C (10% above average ambient temperature). The purpose of simulating in a 10% above average ambient temperature is to ensure the design air flow rate could maintain the tunnel internal temperature even if global temperature rise in future. In total, 8 scenarios have been simulated. From the analysis results, it can be conclude that the most suitable ventilation method is Longitudinal Ventilation for such length cable tunnel. The most suggested inlet air velocity is 0.9055m/s (20ACH) with the air flow of 23470.56 CMH. With this setup, the internal ambient air temperature below 40°C can be achieved. At this temperature, the heat generated by high voltage cables can be dissipated efficiently and maintain in a high performance current carrying capacity.

ABSTRAK

Kajian ini menekankan penggunaan kaedah berangka untuk menentukan kaedah pengudaraan terbaik dan kadar aliran udara terbaik untuk sistem pengudaraan Terowong Bawah Tanah Maju. Tujuan sistem pengalihudaraan mekanikal ini adalah untuk membuang penghasilan haba oleh kabel ketegangan yang tinggi di dalam terowong kabel tanpa wayar ini dan pada masa yang sama mengekalkan suhu dalaman terowong kabel di bawah 40°C untuk memastikan keadaan operasi keadaan mantap. Dalam panjang 163m panjang, 3m lebar dan 2.4m tinggi terowong kabel segi empat tepat, terdapat 4 litar XLPE 132KV 3x1C 1000mm (konduktor tembaga) dipasang di terowong kabel ini dan setiap litar dipasang dalam konfigurasi trefoil. Dengan pengiraan analisis, suhu permukaan kabel XLPE adalah lebih kurang 56.25°C. Walau bagaimanapun, suhu permukaan 60°C untuk digunakan dalam simulasi untuk mensimulasikan senario kes terburuk. Perisian CFD - ANSIS fasih digunakan untuk simulasi dan dipratetap untuk mensimulasikan dalam Kondisi Steady State. Simulasi dijalankan dalam dua jenis kaedah pengudaraan konvensional iaitu Ventilasi Bujur dan Pengalihan Semi Lurus. Dua kadar perubahan udara yang berbeza, 10 Perubahan udara sejam (ACH) dan 20 ACH telah digunakan untuk mensimulasikan dengan dua suhu ambien yang berbeza, iaitu 33.63°C (suhu purata ambien di Lembah Klang) dan 37.00°C (10% di atas purata suhu ambien). Tujuan simulasi dalam 10% di atas suhu ambien purata adalah untuk memastikan kadar aliran udara reka bentuk dapat mengekalkan suhu terowong dalaman walaupun suhu global meningkat pada masa akan datang. Secara keseluruhan, 8 senario telah disimulasikan. Dari hasil analisa, dapat disimpulkan bahawa metode ventilasi yang paling sesuai adalah Ventilasi Longitudinal untuk terowong kabel panjang tersebut. Halaju udara masuk yang paling disyorkan

ialah 0.9055m/s (20ACH) dengan aliran udara 23470.56 CMH. Dengan persediaan ini, suhu udara ambien dalaman di bawah 40°C boleh dicapai. Dengan suhu ini, haba yang dihasilkan oleh kabel voltan tinggi boleh diusir dengan cekap dan mengekalkan dalam kapasiti penyimpanan semasa yang tinggi.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor, Associate Prof. Ir. Dr. Nik Nazri Bin Nik Ghazali, who gave me a lot of advices when I was facing some problems and he guided me throughout the whole project. Associate Prof. Ir. Dr. Nik Nazri Bin Nik Ghazali had shared a lot of opinions with me on how to resolve the problems in my project, and also the things which I should consider in designing my project. His ideas and advices have helped me a lot in guiding me to complete my project.

Furthermore, I also would like to thank all my friends and seniors who have contributed a lot of experiences and guidance for me to finish my project. It helped me to gain a lot of treasure experiences during my hard time when doing my project.

Besides that, I would like to thank my family and my girlfriend Jean who has been giving me fully support to let me to have a great education in University of Malaya for my Master Degree in Mechanical Engineering.

Finally, I would like to thank everyone who gave me advices and supports when I was facing problems and I would like to thank my friends and family for encouragement as motivation for me to finish my project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

XLPE	:	Cross-Linked Polyethylene Cable
HT	:	High Tension
CFD	:	Computational Fluid Dynamics
$\dot{Q}$	:	Flow Rate
A_s	:	Cable Surface Area
M	:	Mass
W	:	Power
V or kV	:	Voltage or Kilo-Voltage
I	:	Current
k	:	Thermal Conductivity
ρ	:	Density
ACH	:	Air change per hour
CFM	:	Cubic feet per minute
CMH	:	Cubic meter per hour
C_P	:	Specific heat in constant pressure
v	:	Kinematic viscosity
Pr	:	Prandtl Number
Re	:	Reynolds Number
R	:	Resistance
D_h	:	Hydraulic Diameter
Nu	:	Nusselt Number
h	:	Convection coefficient
Vol	:	Volume
ΔT	:	Temperature difference

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background

In Malaysia, electricity was transmitted over the mountains by 132kV overhead lines. With the development of Malaysia, overhead lines were unsightly, and their existence has restricted large corridors of land from future development, the government was not in favor of building more overhead lines in Malaysia. Underground cables therefore became the only practical choice. Traditionally, underground transmission cables are installed under the carriageways and there are two types of underground cables installation method which are direct burial (trenches) or cable tunnel. In view of the narrow roads in Malaysia and the many existing underground services, the traditional trenches would often cause severe traffic interruption and great inconvenience to the public as well as visual disruption to residences. To overcome these adverse impacts, local power authority has begun to study the feasibility of using cable tunnels in the planning of new transmission system projects. Table 1 was provided to have a better understand some advantages of cable tunnel against direct burial (trenches).

Table 1: Cable Tunnel vs Direct Burial (Trenches)

	Direct Burial (Trenches)	Cable Tunnel
1	**Higher capital expenditure for insulation** As the soil is a high thermal conductivity material, it would increase the capital expenditure for insulation for the trenches.	**Lower capital expenditure for insulation** While the thermal conductivity of air is lower, the insulation cost would be lesser for the power cables.
2	**Less capability for future expansion** New types of system network require new trenches to accommodate them.	**High capability for future expansion** Cable tunnel is built to cater future expansion. Even new cable lines implemented or any upgrading works, it can be easily installed in the designated cable tunnel.
3	**Difficult for maintenance** Maintenance of system network requires digging and restore the trenches. If the trenches happen to be on the roadbed, this lead to the	**Easy for maintenance** Maintenance personnel enter cable tunnel thru designated access manhole for maintenance. Maintenance operations run below the roadbed, it

	road users will suffer in the traffic jam due to the roadworks.	will greatly reduce the back effect to the traffic.
4	**Difficult location of infrastructure** Hard to trace back the location of trenches. Precise location records for older trenches normally were not provided and not well maintained. In results, site utility mapping and survey required to be conducted which leads to extra expenses.	**Easy location of infrastructure** Easy to coordinate between different infrastructure as its

High tension 132KV operating cable line usually generates a lot of heat while transmitting high capacity of electricity. Without proper ventilation system, electricity cables will suffer and lower down its efficiency. Not only that, maintenance personnel in the cable tunnel will suffer of the work place environment and the chances of causing fire incident increases too. For examples, the cable tunnel fire happened in London Holborn which caused by the electrical fault has resulted a massive threat to the life safety and a long business interruption for 36 hours. The consequences of cable tunnel fire are tremendously huge and it shall not be underestimated. Therefore, an ideal mechanical ventilation system shall be properly be designed can not only ensure a steady operating environment for high voltage cables but can also reduce the potential fire risk in the cable tunnel.

1.2 Problem Statement

In order to have a proper and complex mechanical ventilation system design for the high voltage cables to operate at its best performance, local power authority has been appointed a research institution to conduct a detail study and CFD simulations for a cable tunnel ventilation system design in one of their 132KV high tension cable project. This designed cable tunnel to be simulated is planned to be constructed in Klang Valley area. The designed cable tunnel is a rectangular hollow tunnel with 163 meters length, 3 meters width and 2.4 meters height. As information provided from the client, 4 circuits of 132KV XLPE (cross-linked polyethylene cable) will be installed inside the tunnel and the heat dissipation for each circuit will be roughly 120W/meter. Besides that, the client has requested that the designed mechanical ventilation system must be able to maintain the cable tunnel temperature to be less than 40^{o}C. This is crucial to the client because the overheating of high voltage cables would lead to power transmission performance decreases and cable insulation deteriorate. Subsequently, it will also affect the operating costs too. Therefore, the researcher must determine the required air flow rate and required air change to remove the heat dissipated by 132KV XLPE cables efficiently as well as maintain the cable tunnel temperature below 40^{o}C.

1.3 Project Objective

The designed mechanical ventilation system will perform efficiently in removing the heat disperse from the 132KV high voltage cable.

1) To design and analyze the heat transfer between the 132 KV high voltage cables and surrounding air in tunnel.
2) To determine how air velocity and air change affects the ambient temperature in cable tunnel.
3) To determine how different types of ventilation system affect the performance in heat removing process.

1.4 Project Scope

1. To use CAD software - Solid Works to draw a 3D cable tunnel with 4 circuits of 132KV cables.
2. To use CAD software - Solid Works to design different types of ventilation system into the cable tunnel.
3. To use CFD software – Ansys Fluent to simulate the require air change rate, air speed and air flow volume to achieve heat removing process under steady state heat transfer conditions.
4. To establish the most suitable mechanical ventilation system design and the best air flow to remove the heat dissipated by cables.

CHAPTER 2: LITERATURE REVIEW

2.1 High Voltage Power Cables

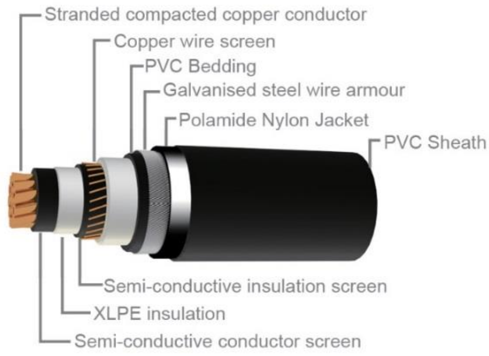


Figure 1: Anatomy of a standard XLPE insulated cable

(Source from: Cable Distribution Services Catalogue, AU)

There are various types of cables available in the market such as PVC cable, EPR cable and XLPE cable etc. However, when it comes to underground application with transmission of 132kV High Tension (HT) electricity, XLPE cable is the preferred choice. This is because it has the feature of excellent insulation.

XLPE also Crosslinking polymers is actually a thermosetting resins. In the process of crosslinking of these thermosetting resins with addition of chemicals or initiators such as silane or peroxide, it changes the molecular structure of the polymer chains so that they are more tightly bound together. This crosslinking process had made XLPE to have better resistant to chemical reaction and does not soften at high temperatures. It develops resistance to stress cracking and ageing. In line with crosslinking of PE to become XLPE, it also increase the temperature range of insulation while maintaining the excellent dielectric strength and a low dissipation factor at all frequencies.

In contrast, XLPE insulated cables have higher current rating and longer service life compared to PVC insulated cables. Under short circuit condition, this cable can withstand up to 250ºC temperature compared to 160ºC for PVC cables.

2.1.1 Heat and Temperature affect Cable Performance

During XLPE insulated cables transmitting high voltage, it will generates tremendous heat. The heat conducted through the layers (as demonstrated in Figure 2.2) and emit out to the surrounding air. This forms a heat transfer effect between the cables and the ambient air via heat convection. It is crucial to have this cooling effect to be happen as the cable temperature would affect the cable carrying capacity performance. There are two fundamental reasons that could explain why temperature will affect cable current carrying capacity reduced are *(i)* metal resistivity in relation to temperature and *(ii)* insulation deterioration.

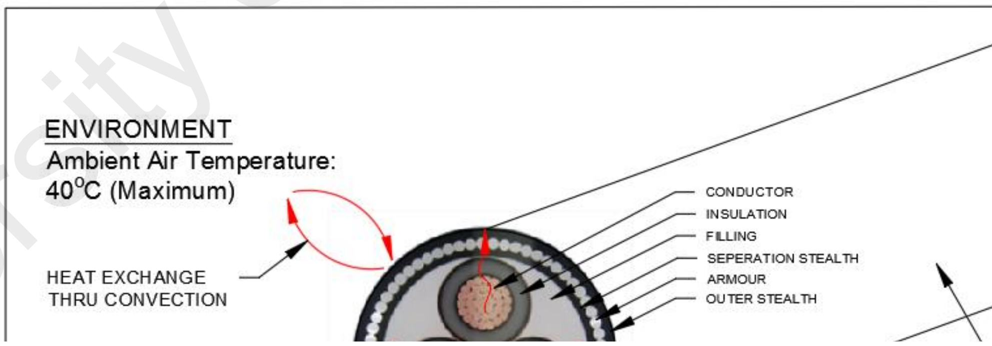


Figure 2: Heat Transfer Mechanism thru Open Air

2.1.1.1 Metal resistivity in relation to temperature

Electrical resistance of a conductor (e.g copper wire / aluminum wire) is dependent on its internal collisional processes within the wire. The resistance value would be expected to be increase proportionally with temperature as there will be more metal collisions happening inside the wire. A temperature coefficient equation has been used to describe the relative change of resistance that is associated with a given change in temperature:

$$\frac{\Delta R}{R_0} = \alpha \Delta T$$

α = Temperature coefficient of resistance

ΔT = Temperature difference

ΔR = Electrical resistivity difference

R_0 = Electrical resistivity at origin

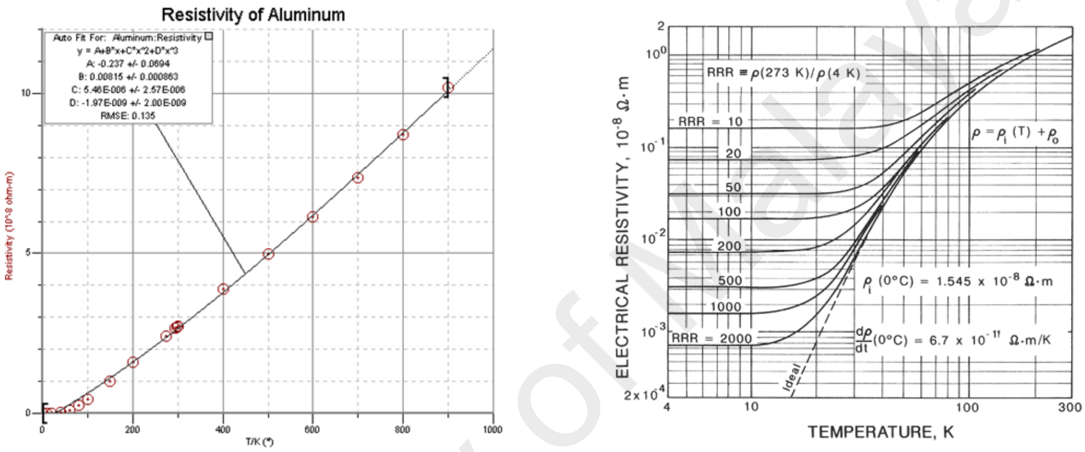


Figure 3: Copper Electrical Resistivity vs Temperature.

(Source from: Copper Development Associate Inc, U.S.)

RRR is defined as the ratio of the room temperature (T= 300K) electrical resistivity to the residual electrical resistivity pR measured at the normal boiling point (T=4.22K). Regardless to whichever RRR it is, the graph shown that the electrical resistivity increases proportionally to the temperature. Therefore, it is important to maintain the temperature

2.1.1.2 Insulation Deterioration

During XLPE insulated cables transmitting high voltage electricity, XLPE insulated cables are permanently subjected to thermal stress (temperature), which can cause an irreversible damage of the cables insulation. The thermal stress called also thermal aging is known as one of the significant phenomenon prevailing in insulated cables under service conditions. The normal operating temperature of the XLPE cable insulation in steady state conditions is considered to be 90°C. The maximum temperature up to 150°C is allowed in overload and up to 250°C in short circuit conditions but it could only withstand for short duration. When aged in service conditions for a period of time, the electrical and mechanical properties of the XLPE insulation may degrade, which may lead to an apparent deterioration in dielectric performances such as electric conductivity, permittivity, dielectric loss and dielectric strength. Subsequently, it may increase the cost of operation and also decrease the life span of the power cables.

2.1.2 Cable installation affect heat dissipation

The arrangement method of cables will affect the heat dissipation efficiency and the current carrying capacity too. Generally there are two types of cable arrangement which are trefoil formation and flat formation as displayed in the figure below. Flat formation usually has been used for cables above 132kV; while trefoil formation has been used for cables under 132kV. It is important to know the cable arrangement and the heat concentration area so the mechanical ventilation system can be designed to tackle these particular heat concentrated area.

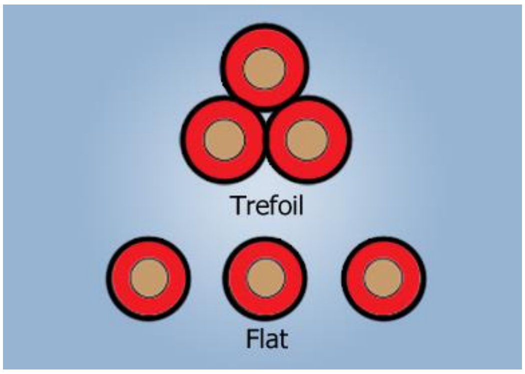


Figure 4: Single Core Cable Installation Method (Source from: ETS Cable Components, UK)

2.1.2.1 Trefoil Phase Formation

Trefoil phase formation is more commonly used because this installation method is much easier and consume less space compared to flat formation. The same distance apart between each cables phase also benefits the magnetic field and circulating currents to be more balanced. However, single-core cables installed in trefoil formation also means that the cables contact with each other will experience poor heat-dissipation compared to flat formation. Subsequently it will lower down the current-carrying capacity. Therefore, electrical design engineers usually include derating factors based on the installation conditions such ambient air temperature / buried soil temperature, grouping or bunching of cables, soil thermal resistivity etc. Whereas for mechanical design engineers shall concern not only on the surface temperature of the trefoil cables but also the intersected area temperature. The design of mechanical ventilation system shall base on the highest temperature which is located at the intersected area.

2.1.2.2 Flat Phase Formation

Flat formation rarely been used in below 132KV power transmission line because it is very space consuming and it required sufficient space at the mounting center for heat-dissipation. In flat formation arrangement, the middle phase cable is adversely affected by the magnetic fields between the neighbor phase cables, which lead the middle phase cable being situated in high temperature environment. Subsequently this has led to the voltage and current carrying capacity imbalance issue. Although phase transposition can resolve this issue, but it is necessary to allocate sufficient mounting space for heat dissipation. The requirement of spacing has been cleared defined in IEC standard 4126/05.

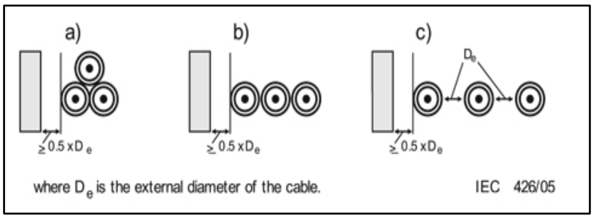


Figure 6: IEC Spacing requirement for single core cable in air (Source from: IEC60228)

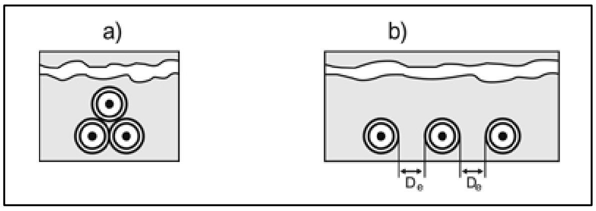


Figure 5: IEC Spacing requirement for single core cable buried directly (Source from: IEC60228)

2.2 Cable Tunnel Cooling System

In order to achieve the required steady operating environment for high voltage cables operation in the cable tunnel, a degree of forced cooling is necessary. A number of alternative cable tunnel cooling system are available, including air cooling (ventilation) system and water cooling system. Air cooling system uses air as the heat transfer medium; while water cooling system uses water as the heat transfer medium. Selecting the type of cooling system is one of the most important decisions when designing a cable tunnel as each types of cooling system has its strength and uniqueness in different types of tunnel. It is critical to pick the most suitable types of cooling system to ensure a consistent and most efficient cooling effect to the cable tunnel.

2.2.1 Air Cooling System

Air cooling system also known as air ventilation system which is used to create air movement to a designated area without reducing it temperature. The following are 5 types of air ventilation system which have been commonly used in the tunnel industry.

(i) Natural Ventilation

(ii) Longitudinal Ventilation System

(iii) Semi Transverse Ventilation System

(iv) Transverse Ventilation System

(v) Point Extraction Ventilation System

2.2.1.1 Natural Ventilation

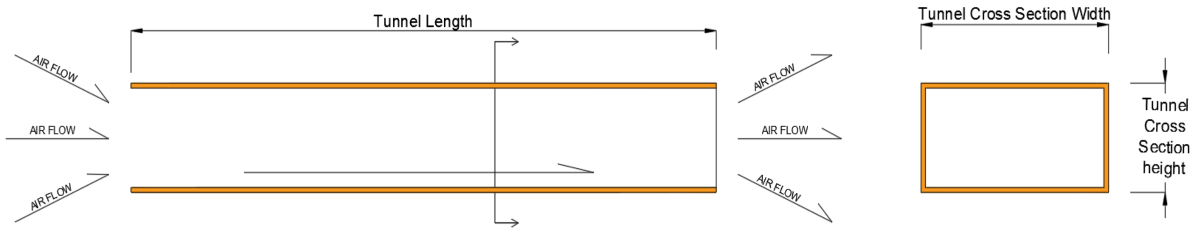


Figure 7: Natural Ventilation

Natural ventilation is a process that supply air to and exhaust air from the tunnel without using energy and mechanical system. This ventilation is highly dependent on the weather aspect such as wind speed, pressure and weather temperature which would affect the efficiency of ventilation. Besides that, natural ventilation also depends on the position and shape of the inlet and outlet ventilation openings to achieve good efficiency. This system normally applied in short vehicle tunnel as it usually rely on traffic piston effect and/or seasonal wind to ventilate the tunnel. In another word, natural ventilation is not suitable to apply on cable tunnel because there is no vehicle happen to be in the cable tunnel and high voltage cables required consistent ventilation to dissipate heat. Furthermore, the surrounding air usually difficult to enter cable tunnel as it used to be built underground and mostly enclosed to ensure water tight condition.

2.2.1.2 Longitudinal Ventilation System

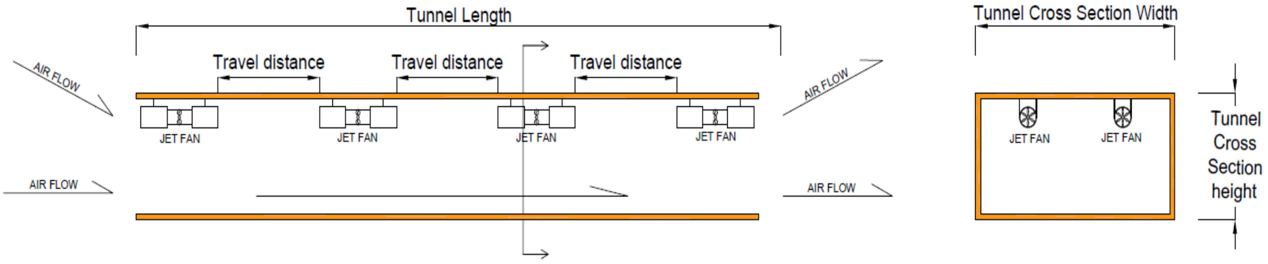


Figure 8: Longitudinal Ventilation System

The simplest form of mechanical ventilation is longitudinal ventilation. Longitudinal ventilation system utilized jet fan or axial fans at the entry of portal to induce a large volume of fresh air into the tunnel. The fresh air pass through the entire tunnel and exit at the other end of tunnel. The mechanical fans are usually installed at both end of the tunnel. This system usually designed for those tunnel which have insufficient space for ducting. Therefore, the tunnel itself has become a channel to carrying fresh air from one end to another end. This feature has made it easy for construction and maintenance as the absent of duct work. This system usually apply to short tunnels, however for long tunnel, it required intermediate fans or booster fans to carry the fresh air to further distance. Besides that, the jet fans also can be programmed to operate in forward direction or reverse direction which made up the flexibility in ventilating the cable tunnel. However, this system is not suitable to be applied for cable tunnel. This is due to the fresh air temperature will increase along the entire tunnel as it carries the heat dissipated by cables thus causes the temperature very high at the exit portal. In results, the cooling effect is very weak at the end part of the cable tunnel.

Figure 9: Axial Fans

Figure 10: Jet fans

2.2.1.3 Transverse Ventilation System

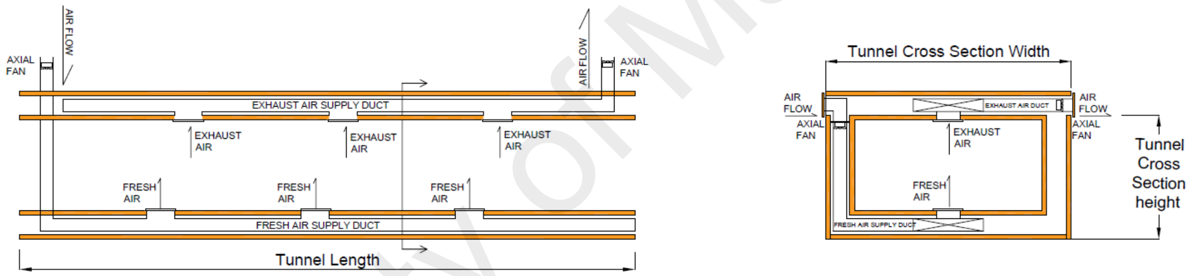


Figure 11: Transverse Ventilation System

Transverse ventilation is different to longitudinal ventilation as it incorporate duct work along the entire tunnel to introduce fresh air and extract the flue air from the tunnel. This two ducts are usually design in different air change rates which create the pressure difference to keep the air flow from high pressure towards the low pressure side. The setup of this duct work system can be at the top and below of tunnel or it can also be installed on the two sides of the tunnel. With the top and bottom duct settings, the exhaust air duct usually been placed at the top the tunnel to increase the heat/smoke rejection efficiency. This is because hot air rises and the fresh air duct at bottom will supply air to push the hot air toward exhaust duct. This system grants the most efficient and safety ventilation to the tunnel because every section of the tunnel also have its own supply air and exhaust air. However, it is also the most expensive ventilation solution as it involves high construction cost. The main reason is that the tunnel required larger cross section area to accommodate ducting.

2.2.1.4 Semi Transverse Ventilation System

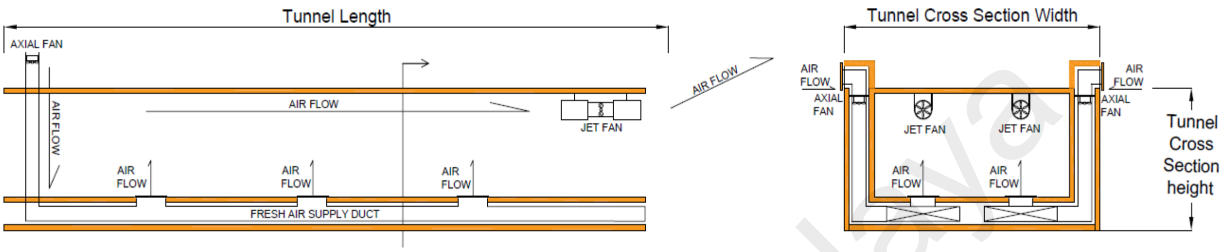


Figure 12: Semi Transverse Ventilation System

Semi-transverse ventilation is a combination of both longitudinal and transverse ventilation method. Generally, there are variations of semi transverse ventilation system set up compared to the other ventilation system.

1. Fresh air can be supplied through the portals with mechanical jet fan or axial fan and be continuously exhausted through a duct along the length of the tunnel. Alternatively fresh air can be supplied through a duct and exhausted through the portals with mechanical jet fan/axial fan.
2. Two jet fans can be installed at both end portal and draw in fresh air into the center of the tunnel, while there is an exhaust duct at the center of the tunnel to extract out all the flue air.
3. Half of the tunnel will be supply air system with ducting at bottom where another half of the tunnel will be with exhaust air system with ducting on top.

As the hot air density is lower than the normal temperature air, even how the setting up varies, the exhaust air duct must be always remain at top of the tunnel to perform a better ventilation. In this research, semi transverse ventilation is a much preferred choice as it heat rejection effect will be much better than longitudinal ventilation system and half the construction cost of transverse ventilation system. The ducting setting No.2 stated above will be incorporate into the cable tunnel to conduct simulation test.

2.2.1.5 Point Extraction Ventilation System

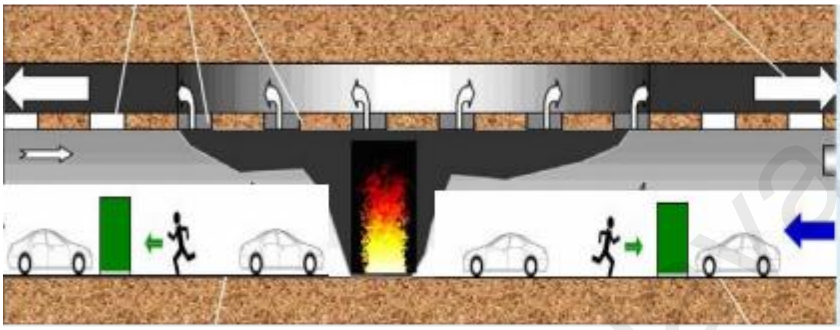


Figure 13: Point Extraction Ventilation System

Point extraction ventilation system usually work together with semi / full – transverse ventilation to be a smoke spill system. In the event of a fire in the cable tunnel, this system is designed to extract smoke at the fire location by keeping the smoke stratification intact, leaving more or less clean and breathable air suitable for evacuation underneath the smoke layer to both sides of the fire. This achieved by zoned transverse ventilation or single point extraction. Typically, this system requires exhaust ventilation ducts and a system capable of localizing hot gases and smoke and extracting them at the fire location using exhaust high temperature rated ventilation fans. Besides that, this system is applicable to bi-directional or congested unidirectional tunnels. However in this research study, fire and smoke is not part of the scope of research and therefore this will not be included in the simulation.

2.2.2 Water Cooling System

Water cooling system is a system that utilize cooled water circulated inside the pipelines to extract the heat generated by power cables to achieve the cooling effect in the tunnel.

Cooled water was manufactured by chiller and pump into the pipeline in tunnel to absorb the heat generated by power cables. Then the water which has absorbed heat will return to the cooling tower to release the heat. This process will be run in continuous cycle until the power cable cooled to its best current carrying capacity temperature. In order to be energy efficient in this process, the water pump will adjust its flow rate based on the amount of heat that need to be removed.

Water cooling system generally have two ways to lay its water pipeline which are indirect cooling method and direct cooling method.

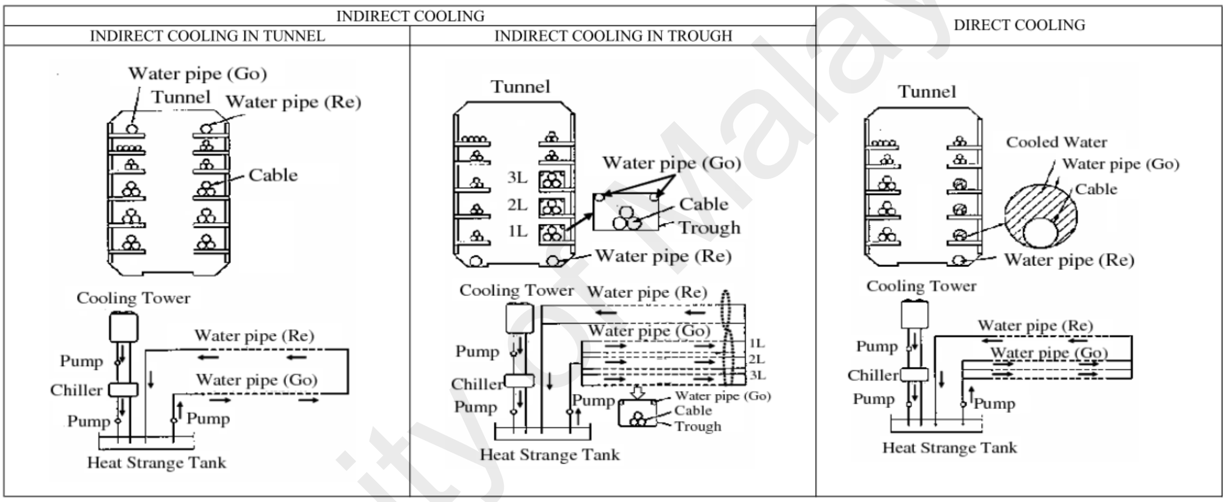


Figure 14: Water Cooling System (Transmission capacity design of underground power cables installed in deep tunnel, Miko Matsumura 2006)

For indirect cooling, this means that the water pipe did not contact directly to the power cable to perform the cooling process. The heat generated by cable initially will transfer to the surrounding air thru convection then conduct to the cooled water pipes. The water pipe can be either lay at the corner of the tunnel or inside the trough. If the water pipes were placed at the corner of the tunnel, it may require longer time to cool the power as it will also cool the surrounding air temperature in the tunnel. Whereas if the water pipes were placed in the trough individual for each circuit of power cables, it takes shorter time to cool the power cables as it do not cool the entire surrounding air in the tunnel. This type of indirectly cooling usually integrated with an air ventilation system to induce air movement to increase its cooling performance. Besides that, a drainage system was installed below the pipeline which function to drain off the condensation water just to prevent it from short circuiting the power cable.

For direct cooling, power cables were installed in the pipeline and the cooled water was direct contact to the power cable surface to perform cooling process. The heat generated by cable will direct conduct to the cooled water. This type of cooling is very effective compared to indirect cooling but it disadvantage is that the water easily sip into the power cable and short circuit occur.

2.3 Analytical Method vs Numerical Method

In solving the heat transfer problems in the cable tunnel, there are generally three types of methods which are experimental, analytical, and numerical. Usually experimental method will not be use because it is very time consuming, costly and less flexibility to handle parameters variations. Thus, the other two methods are going to be applied into this research.

Analytical method solve problems based on governing differential equation together with boundary conditions. It provide the solution function for temperature at every point in the medium. Analytical methods is good at some point because it can provide exact solutions as they do not involve in any approximations. However, analytical method only can solve simplified problem in simple geometries. This method will be used first in order to find out the surface temperature and the approximate forced convection heat transfer rate.

On the other hand, Numerical method is replacing governing differential equation by a set of *n* algebraic equations for the unknown temperatures at *n* selected points in the medium and the simultaneous solutions of these equations results in the temperature values at those discrete points. Although analytical method which provide exact solution is good, but there are many problems encountered in real life practice involve complicated geometries which complex boundary conditions or variable properties which cannot be solved analytically. Whereas numerical methods have become popular with the development of the computing capabilities, and although they give approximate solutions, have sufficient accuracy for engineering purposes. Therefore, after obtaining the pre-calculated data from analytical method and calculations, those pre-calculated data were transferred into the simulations software to proceed numerical calculations.

CHAPTER 3: METHOD STATEMENT

3.1 Data Collection

Due to the architecture design of cable tunnel was pre-designed by the client appointed architects and engineers, several preliminary input data of this cable tunnel project was provided by the client.

Table 2: Data Collection from client

Tunnel type	Unmanned type underground cable tunnel.
Tunnel dimensions	Approx. 163m (L) x 3m (W) x 2.4m (H)
Tunnel sections required mechanical ventilations	Section B (highlighted in yellow)
Tunnel structural construction materials	Concrete & steel bars
Power Transmission	132KV (3 phase)
Type of transmission cables	XLPE Insulated Cables
Maximum continuous conductor temperature	90°C
Number of circuits installed in the tunnel	4 sets of 3x1C 1000mm^2 XLPE cables
Cable arrangement	Trefoil
Estimated heat dissipation of each circuit	120W/metre
The target design internal temperature of cable tunnel	below 40°C

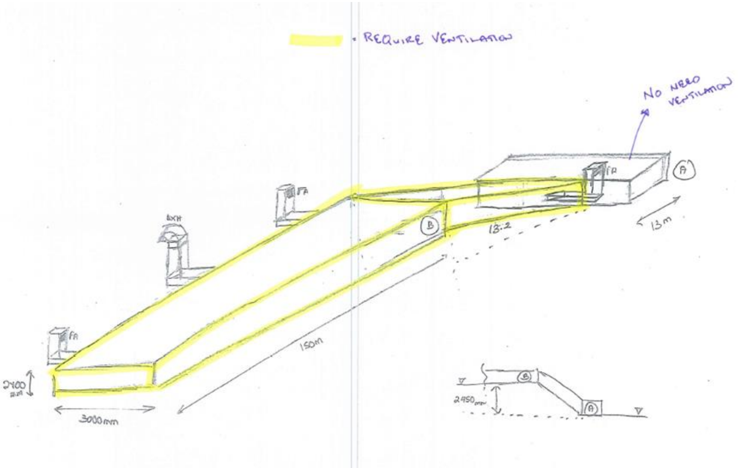


Figure 15: Hand sketch Tunnel & Ventilation System design

3.2 Design Considerations

With the preliminary data collected from client, the main focus in this study is to utilize the mechanical ventilation to remove the excessive heat dissipated by the high voltage cables in the tunnel section B and maintain the tunnel internal temperature below 40^{o}C. Several design considerations for the mechanical ventilation system shall be take into account before kick starting the research.

1. Types of mechanical ventilations system to be applied for comparison: Longitudinal Ventilation vs Semi Transverse Ventilation
2. The intake air shall base on **highest** ambient temperature at Klang Valley for the year.
3. The position and number of the fresh air intake and exhaust air to be pre determine before CFD simulation.
4. The fresh air inlet and exhaust air outlet size to be pre determine before CFD simulation.
5. The air change rate and the air flow speed required to be pre determine before CFD simulation.
6. Verify whether the air change rate and air flow speed sufficient to remove the heat and maintain the tunnel internal temperature below 40^{o}C.

Exclusion from the design consideration:

1. The mechanical ventilation system did not take into consideration of smoke exhaust scenario as this research is focusing only on heat transfer problems.

3.3 Meteorology Weather Data in Klang Valley

The designed mechanical ventilation system will draw outside air (heat transfer medium) into the cable tunnel to carry heat out from tunnel. Therefore, it is important to know the temperature of the outside air that the system draw into the cable tunnel. If the weather temperature is higher than 40°C (the ambient temperature limit in cable tunnel),

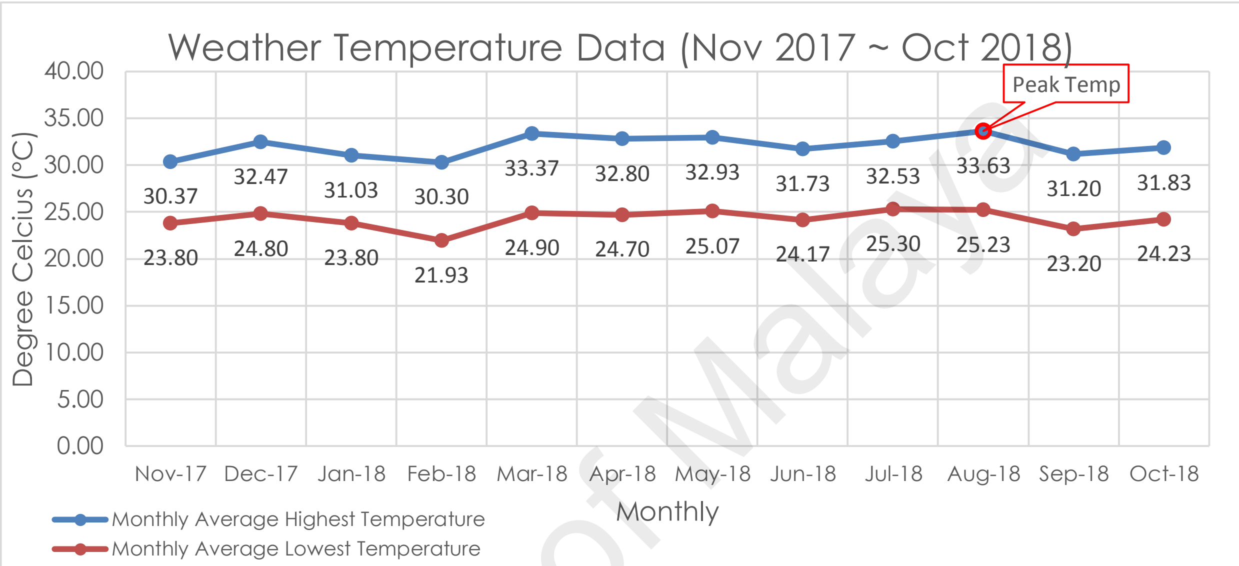


Figure 16: Weather Temperature Data (Nov 2017 ~ October 2018)

the draw in air required to be pre-cooled before entering the cable tunnel; whereas if it is below 40°C, no pre-cooled is required.

The above weather temperature data was extracted from the data provided by official Malaysia Meteorology Department website. By analyzing the weather data for a year in Klang Valley, the average highest temperature falls between 30.30°C ~33.63°C. With this data, the draw in temperature of outside air. The input data for the CFD simulation shall be based on the worst case scenario (33.63°C). However, a 10% safety factor on top of the worst case scenario (37 °C) shall be simulated too due to the global warming effect.

3.4 Analytical solutions under Steady State Condition

Several pre-calculation are necessary to be done before entering modelling and simulation stage as it would produce the preliminary design for the mechanical ventilation system. With these analytical formulas and solutions, it could give a rough estimation that what are the values to be applied into the simulation parameters such as inlet and outlet air velocity, inlet and outlet area etc.

3.4.1 Step 1 – Assumptions to be made

1. Steady operating conditions exist.
2. The outer surface temperature of the cable is uniform at all time.
3. Thermal conductivities are constant.
4. Radiation effects are negligible.

3.4.2 Step 1 – Calculate heat generation from power losses/voltage drop

$\dot{Q} = W_e = V \times I$

V = Voltage Drop (Usually less than 3% of 132kV, in this case we assume 1.5%)

I = Maximum current capacity flow in the 1000mm^2 XLPE cable

D_F = Derating factor (Assume a 80% of D_F according to the installation method)

$\dot{Q}$ = 132000 V x 1.5% x 1230A x 0.8

$\dot{Q}$ = 1948320W = 1.948MW

3.4.3 Step 2 – Calculate Thermal Resistance of XLPE Cables

Table 3: XLPE cable properties

Material	Thermal Conductivity, k (W/mK)	Density (kg/m3)	Diameter (mm)	Thickness (mm)
Copper Conductor	400	8700	38.2	-
Copper Screen	400	8700	-	1.5
XLPE Insulations	1/3.5	1380	-	14.7
XLPE Insulation Screen	1/3.5	1380	-	1.5
Aluminium Metallic Sheath	215	2700	-	0.8
PVC Outer Sheath	0.2	1760	-	3.6

Estimated diameter for each 1C cable	82.4	
Estimated diameter for trefoil arrangement for 3 x 1C cable	193	

R conduction = $\dfrac{\ln(\frac{R_1}{R_2})}{kA_s}$

As = 2πRL (surface area of cable)

k = Thermal Conductivity

L = Length of cable

Table 4: Total conduction resistance of XLPE cable

	Material	K (W/mK)	Radius (mm)	L (m)	π	R (°C/W)
R1	Copper Conductor	400	19.1	163	3.142	
R2	Copper Screen	400	20.6	163	3.142	1.85E-07
R3	XLPE Insulation	4	35.3	163	3.142	1.31E-06
R4	XLPE Insulation Screen	4	36.8	163	3.142	1.02E-05
R5	Aluminium Metallic Sheath	215	37.6	163	3.142	5.25E-06
R6	PVC Outer Sheath	0.2	41.2	163	3.142	4.15E-07
				$R_{conduction}$ Total		1.73E-05

3.4.4 Step 3 – Calculate surface temperature of cables

Generally XLPE cable have been rated its continuous current carrying capacity at its maximum conductor temperature of 90°C. Therefore, the conductor temperature (T_1) has been assume as it maximum allowable temperature which is 90°C.

The cable surface temperature at steady state conditions can be determined from the below equation:

$$\dot{Q} = \frac{T_1 - T_2}{R_{conduction}}$$

$T_2 = T_1 - (Q \times R_{conduction})$

$T_2 = 90^oC – (1,948,320 \times 1.73 \times 10^{-5})$

$T_2 = 56.25^oC$ #

3.4.5 Step 4 – Calculate the convection coefficient of forced convection heat transfer over a circular cross section cable

Ambient temperature: 33.63ºC

Cable Surface Temperature: 56.25ºC

Average film temperature: $\frac{T_S + T_{ambient}}{2} = \frac{56.25+33.63}{2} = 44.62^oC$

The properties of air at average film temperature: (obtained from Table A-15)

k = 0.02699 W/m.K

Pr = 0.7241

ν = 0.0000175 ms^{-2}

V = 2.00 m/s

The hydraulic diameter of the rectangular tunnel can be determined from the below equation:

$D_h = 2 \times W \times H / (W + H)$

$D_h = 2 \times 3.0 \times 2.4 / (2.4+3.0)$

$D_h = 2 .6667$metres

The Reynolds number for the forced convection heat transfer can be determined from the equation below:

$$Re_D = \frac{VD_h}{v}$$

$$Re_D = \frac{2.00\ x\ 2.667}{0.0000175}$$

$Re_D = 304,762$ (Re_D falls between 40,000 - 400,000)

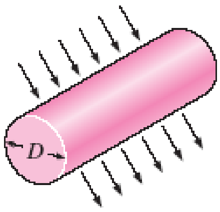
Cross-section of the Cylinder	Fluid	Range of Re	Nusselt number
Circle 	Gas or Liquid	0.4 – 4	$Nu = 0.989\ Re^{0.330}Pr^{1/3}$
		4 - 40	$Nu = 0.911\ Re^{0.385}Pr^{1/3}$
		40 - 4000	$Nu = 0.683\ Re^{0.466}Pr^{1/3}$
		4000 - 40,000	$Nu = 0.193\ Re^{0.618}Pr^{1/3}$
		40,000 - 400,000	$Nu = 0.027\ Re^{0.805}Pr^{1/3}$

Figure 17: Empirical correlations for the average Nusselt number for forced convection overcircular in cross flow (Zukauskas, Ref 14 and Jakob, Ref 6)

The Nusselt number for the forced convection heat transfer over a circular cross section cable can be determined from the equation below:

$$Nu = \frac{hD}{k} = 0.027\ Re_D^{0.805}\ (Pr^{1/3})$$

$$Nu = 0.027 \times (304762^{0.805}) \times (0.7241^{1/3})$$

$$Nu = 629.83$$

$$Nu = \frac{hD}{k}$$

$$h = \frac{Nu \times k}{D}$$

$$h = \frac{629.83 \times 0.02699}{2 \times 0.0412}$$

$$h = 206.30\ W/m^2.K$$

3.4.6 Step 5 – Calculate the rate of heat transfer

The cable surface area can determined from the equation below:

No of cables = 4 Set of 3 x 1C = 12 nos of 81.2mm diameter 1000mm^2 XLPE cable

$$A_S = 12 \times 2\pi RL$$

$$A_S = 12 \times (2 \times \pi \times 0.0412 \times 163)$$

$A_S = 506.344 m^2$

The average heat transfer from Newton's law of cooling by using the average surface temperature:

$\dot{Q} = h\, A_S\, (T_S - T_\infty)$

$\dot{Q} = 206.30 \times 506.344\, (56.25 - 33.00)$

$\dot{Q} = 2{,}362{,}858.80 W$

3.4.7 Step 6 - Calculate the time required to cool down the cable temperature

Mass of XLPE cable with full copper conductor

$M = \rho \times Vol$

ρ (Density of copper conductor) = $8960 kg/m^3$

Vol (Volume of 1 no of copper conductor) = $\frac{\pi D^2}{4} L = \frac{\pi\, x\, \frac{82.4}{1000}^2}{4} \times 163 = 0.87 m^3$

$M = 8960 \times 0.87$

$M = 7788$ kg

C_p, specific heat coefficient of copper = 376.812 J/kg.K

Total heat released from the core of conductor to surface:

$Q = 12 \times m\, C_p\, \Delta T$

$Q = 12 \times 7788 \times 376.812 \times (90.00 - 56.25)$

$Q = 1{,}118{,}517{,}802$ J

The time of cooling is determined to be:

$\Delta t = \frac{Q}{\dot{Q}} = \frac{1{,}118{,}517{,}802}{2{,}362{,}858.80} =$ 473.37 seconds = 7.89 minutes.

3.4.8 Step 7 – Repeated same method as above with different ambient air temperature and air flow speed

Step 1 to Step 6 has been repeat with different ambient air temperature and different air speed. The results have been tabulated in the following tables and graphs.

Table 5: Forced Convection Heat Transfer Rate and Cooling Time at Different Air Speed at Ambient Air Temp 33.63°C

Air speed (m/s)	h (forced convection heat transfer rate)	Cooling time, ΔT (min)	Reynolds No
0.4527	62.393	27.711	69022.298
0.5000	67.590	25.580	76234.038
0.9055	109.019	15.859	138059.844
1.0000	118.089	14.641	152468.077
1.0867	126.263	13.693	165687.059
1.5000	163.667	10.564	228702.115
2.0000	206.318	8.380	304936.154
2.1733	220.592	7.838	331358.872
2.5000	246.916	7.002	381170.192

Table 6: Forced Convection Heat Transfer Rate and Cooling Time at Different Air Speed at Ambient Air Temp 37.00°C

Air speed (m/s)	h (forced convection heat transfer rate)	Cooling time, ΔT (min)	Reynolds No
0.4527	62.181	32.672	68373.357
0.5000	67.360	30.160	75517.293
0.9055	108.650	18.698	136761.818
1.0000	117.688	17.262	151034.587
1.0867	125.835	16.145	164129.286
1.5000	163.112	12.455	226551.880
2.0000	205.619	9.880	302069.174
2.1733	219.844	9.241	328243.468
2.5000	246.079	8.256	377586.467

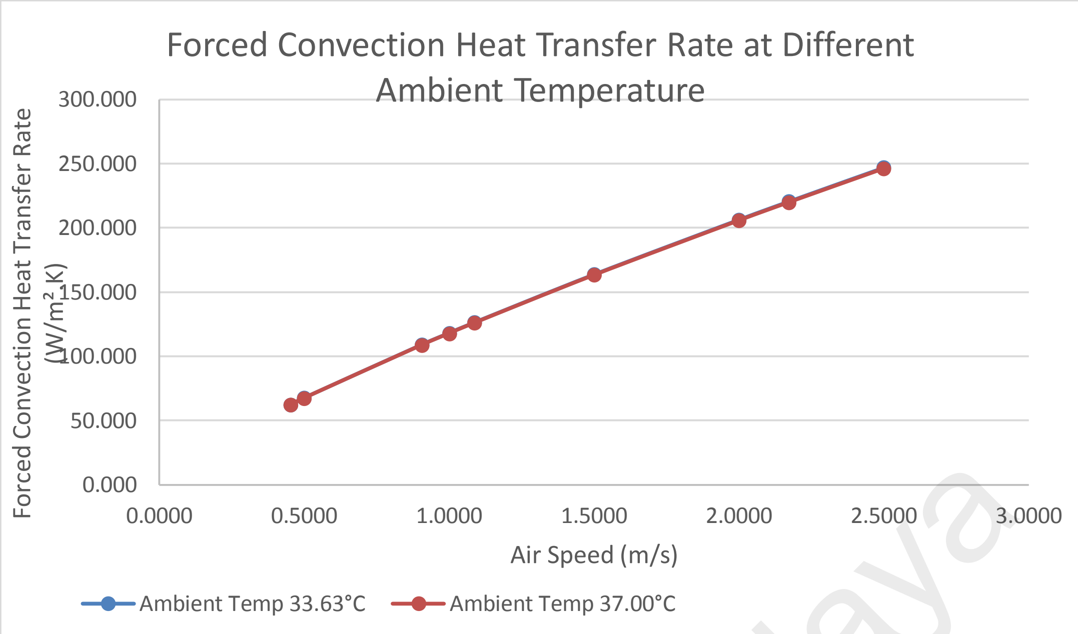


Figure 18: Forced Convection Heat Transfer Rate at Different Ambient Temperature

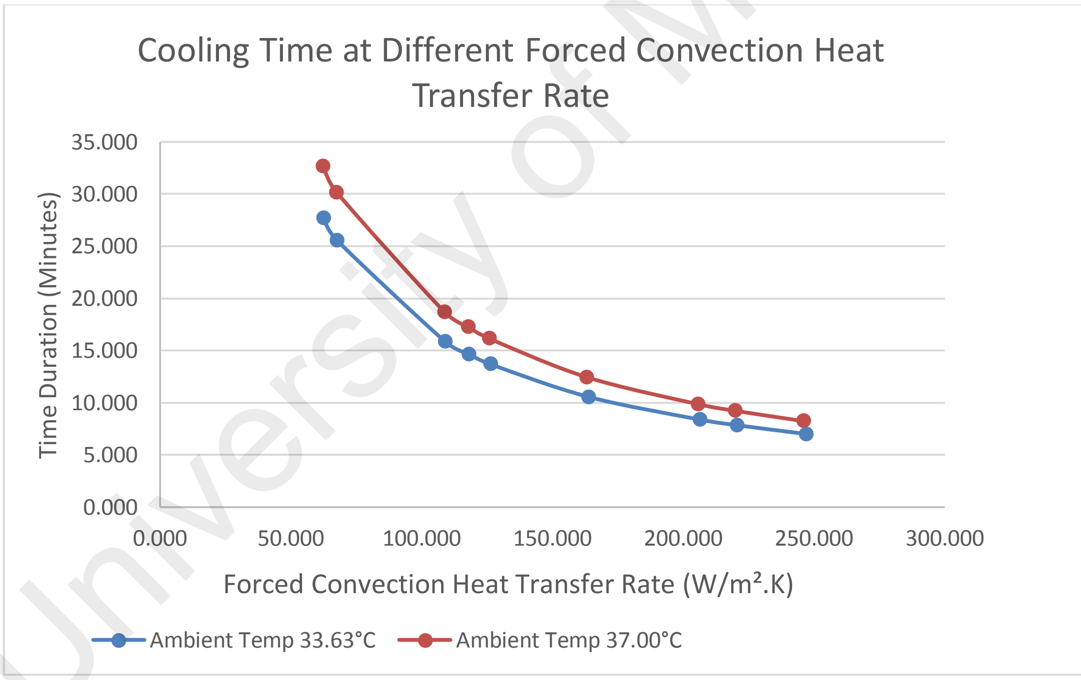


Figure 19: Cooling Time at Different Forced Convection Heat Transfer Rate

All the results, graphs and tables above were calculated from analytical method. From It shown that at higher air speed, the forced convection heat transfer rate is higher too. With higher forced convection heat transfer rate, the cooling time is faster.

Although the input ambient air temperature 33.63°C and 37.00°C seems did not create much difference in the graph, however in figure 18, it shown that the cooling time reduced when forced convection heat transfer rate increase. Besides, the cooling time is lower if the input at lower ambient air temperature.

3.5 Numerical solutions under Steady State Condition

3.5.1 Step 1 - CAD Modeling of the cable tunnel

As mentioned in the literature review, two types of air ventilation method will be used in this simulation which is longitudinal ventilation and semi transverse ventilation. Two underground cable tunnel CAD models were modeled using Solid Works Software to demonstrate the above mentioned two types of ventilation system set up.

1. Model 1 - Longitudinal ventilated underground cable tunnel
2. Model 2 - Semi transverse ventilated underground cable tunnel

3.5.1.1 Model 1 - Longitudinal ventilated underground cable tunnel

This underground cable tunnel CAD model consist 1 supply air inlet at the entry portal and 1 exhaust air outlet at the exit portal. The entire length of the cable tunnel is 163metres. The total tunnel volume is 1157m^3. The area of the air inlet and air outlet are the same which are 3.0metres (W) x 2.4 metres (H). 4 circuits of XLPE cable were placed inside the cable tunnel for simulation. The estimated diameter for each cable is 193mm.

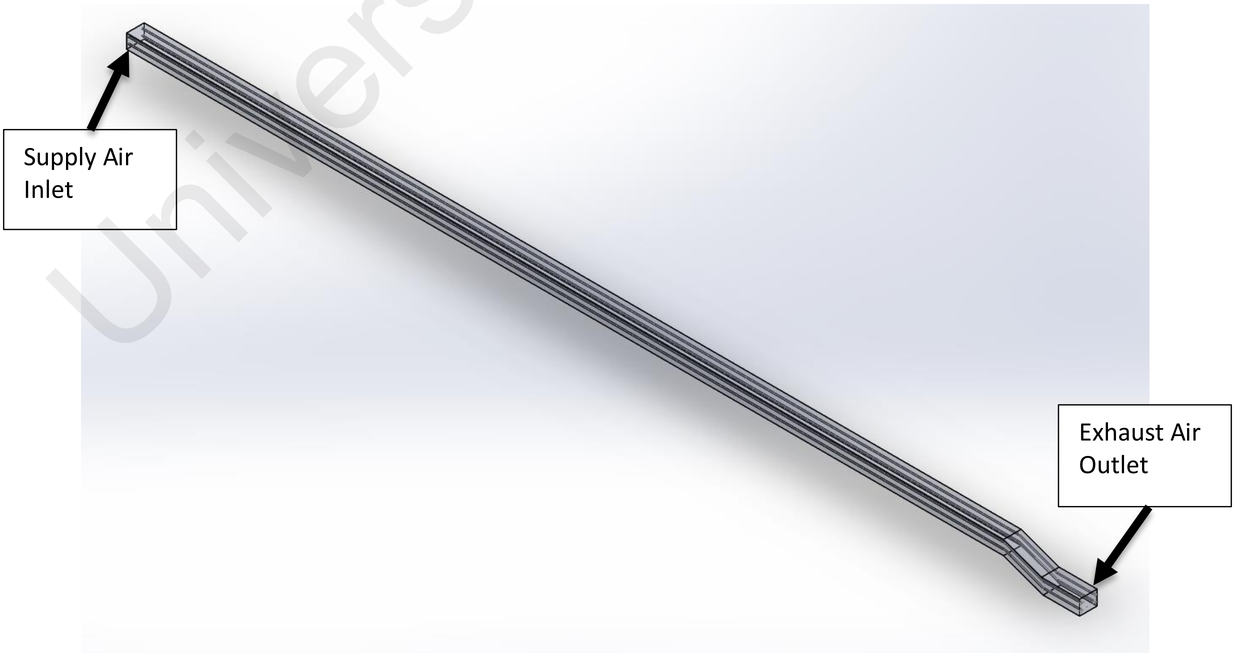


Figure 20: Longitudinal ventilated underground cable tunnel

Figure 21: Side View of Longitudinal Ventilated Cable Tunnel

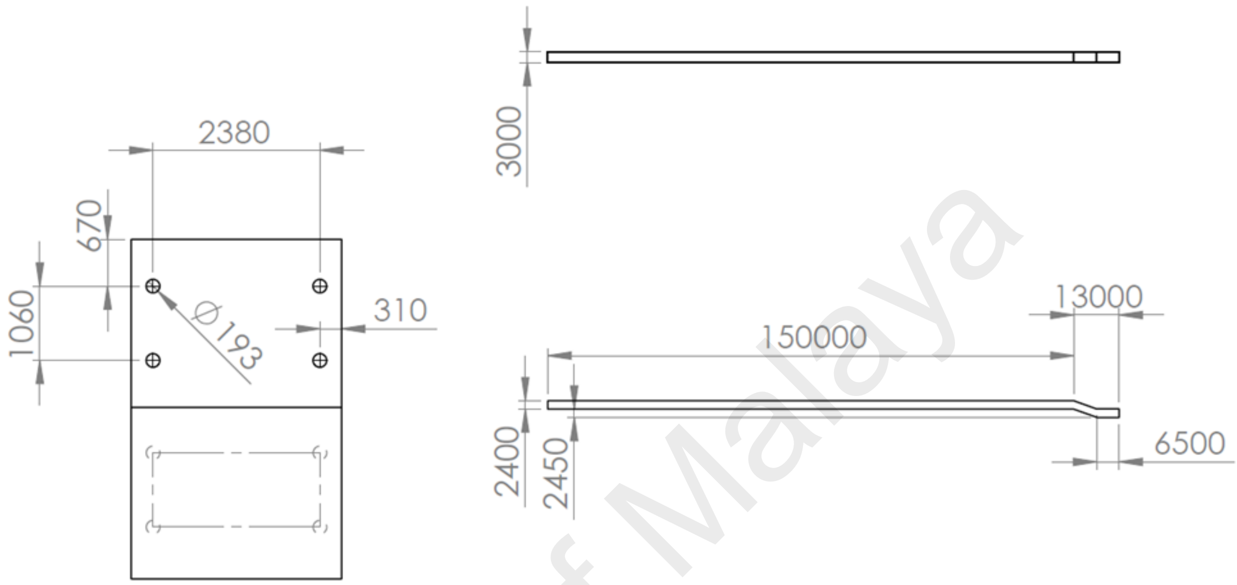


Figure 22: Detail dimension of Longitudinal Ventilated Cable Tunnel

3.5.1.2 Model 2 - Semi transverse ventilated underground cable tunnel

This underground cable tunnel CAD model consist 3 air inlet and 1 air outlet. The entire length of the cable tunnel is 163metres. The total tunnel volume is 1240m^3. The area for each supply air inlet is 1m^2 (1000mm (W) x 1000mm (H)) and exhaust air outlet area is 1m^2 (1000mm (W) x 1000mm (H)). 4 circuits of XLPE cable were placed inside the cable tunnel for simulation. The estimated diameter for each cable is 193mm.

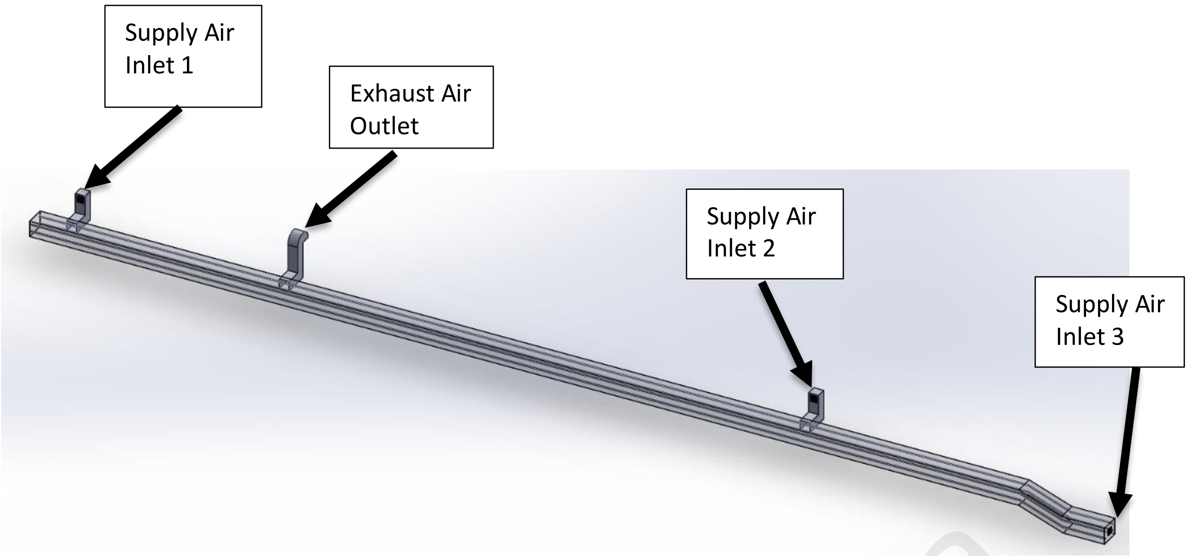


Figure 23: Semi transverse ventilated underground cable tunnel

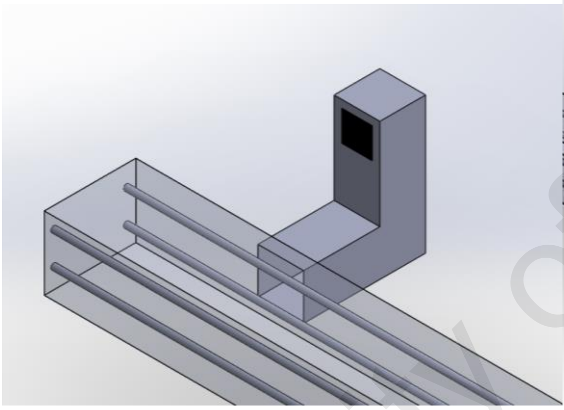


Figure 24: Supply Air Inlet 1

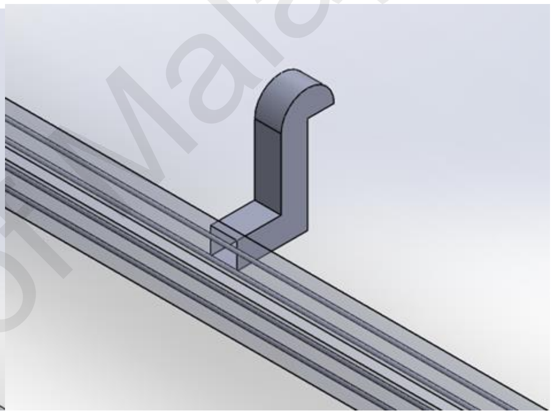


Figure 25: Exhaust Air Outlet 1

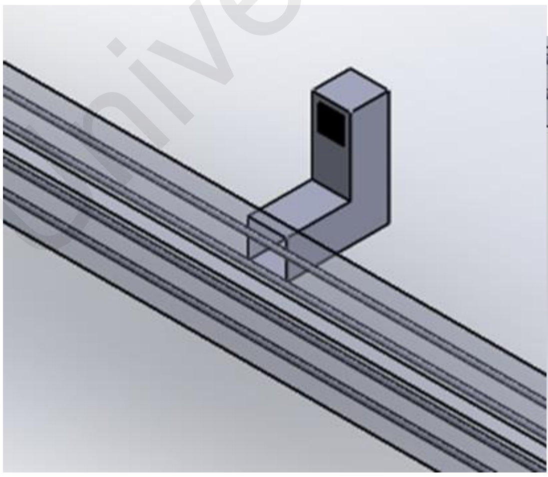


Figure 26: Supply Air Inlet 2

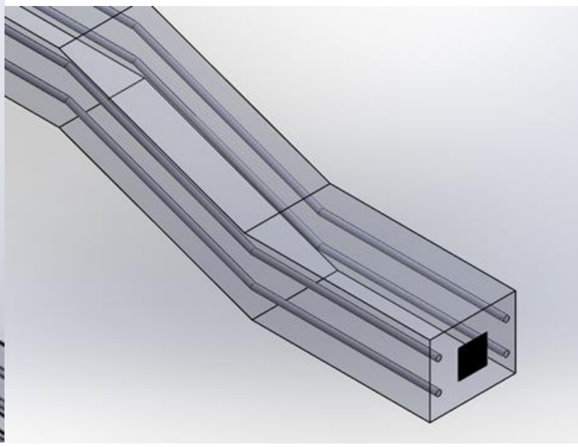


Figure 27: Supply Air Inlet 3

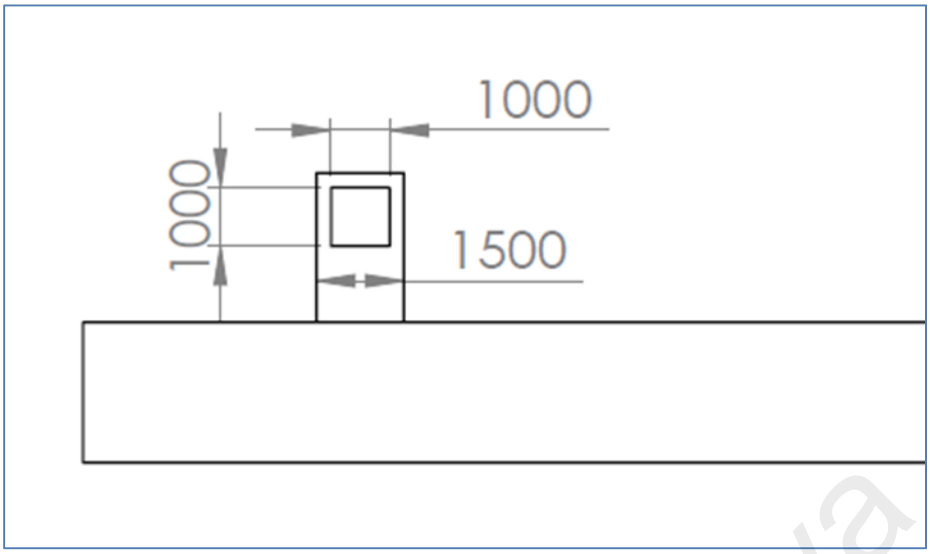


Figure 28: Side View of Supply Air Inlet 1 & 2

Figure 29: Side View of Semi-Transverse Ventilated Cable Tunnel Model

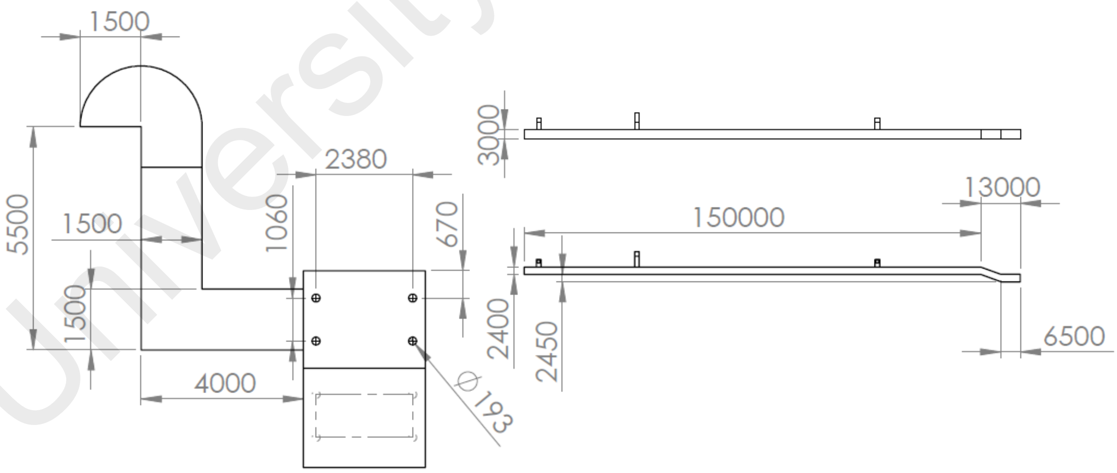


Figure 30: Detail dimension of Semi Transverse Ventilated Cable Tunnel Model

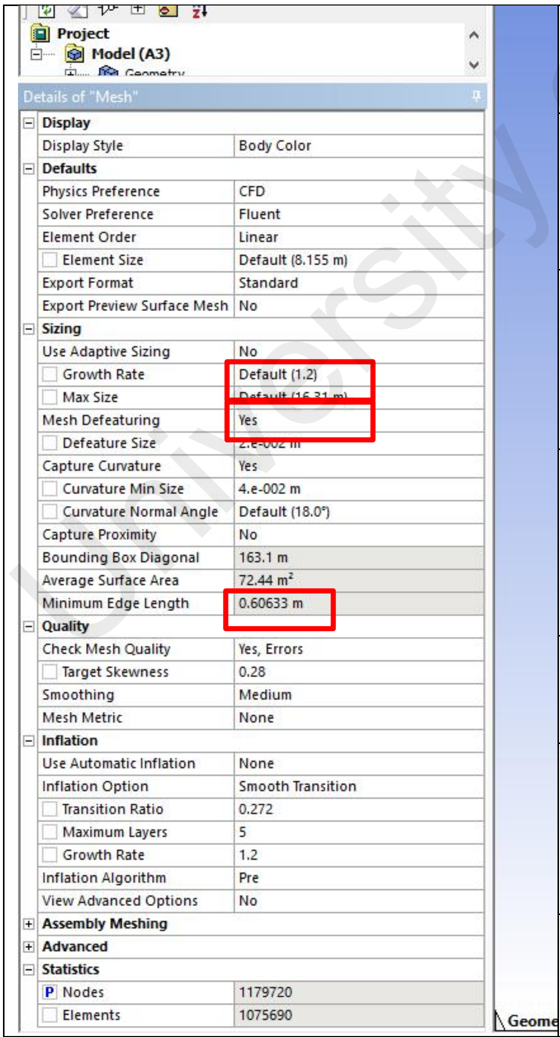
3.5.2 Step 2 - Meshing the cable tunnel

Once the two models have been completely setup in Solid Work Software, it have to be export to ANSYS FLUENT to carry out the simulation. In order to enable the simulation result to be as accurate as possible, the meshing need to be as fine as possible. The finite element mesh is used to subdivide the CAD model into smaller pieces which usually been called “elements”. After that, ANSYS FLUENT will use a set of governing equations to solve each of these elements.

3.5.2.1 Meshing Model 1 - Longitudinal ventilated underground cable tunnel

The meshing setup for model 1 has been tabulated below, while the rest parameters were remain default.

Table 7: Meshing Details for Model 1



Input parameters:	
Min Size (m)	0.02
Max Size (m)	0.04
Average of Skewness	0.28
Output results:	
Number of Nodes	1,179,720
Number of Elements	1,075,690

After the setting up, meshes have been generated for the Model 1 and presented in the below figures.

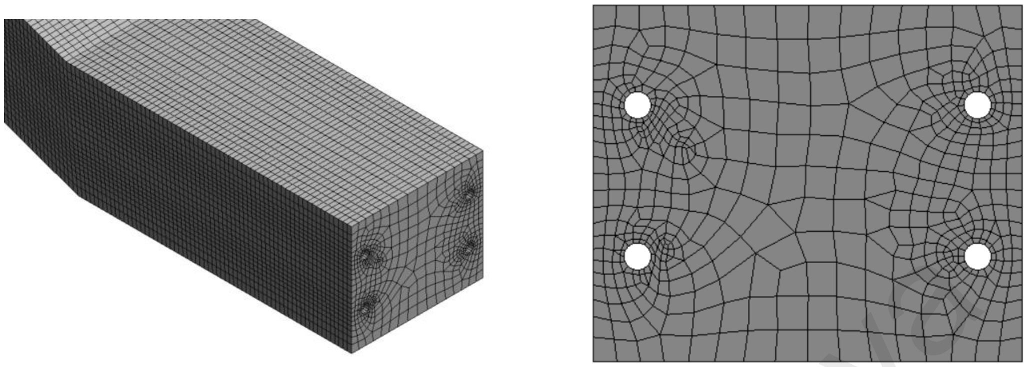
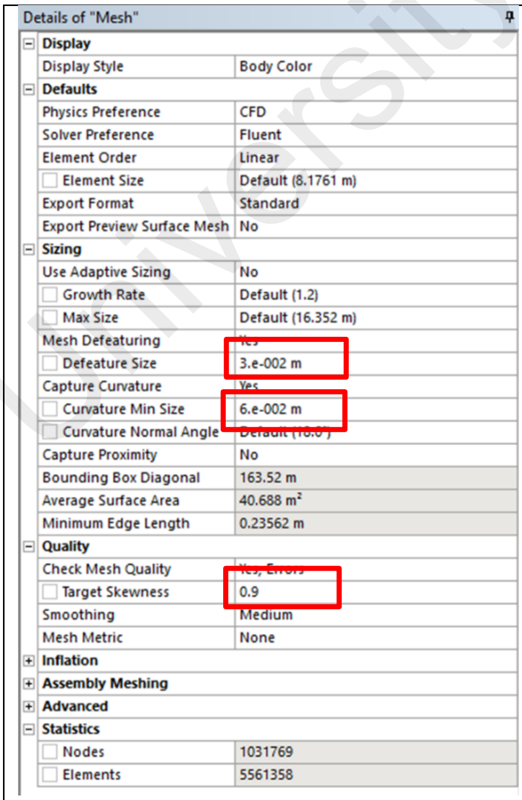


Figure 31: Generated Meshes for Model 1

3.5.2.2 Meshing Model 2 - Semi transverse ventilated underground cable tunnel

The meshing setup for model 2 has been tabulated below, while the rest parameters were remain default.

Table 8: Meshing Details for Model 2



Details of "Mesh"	
Display	
Display Style	Body Color
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	Default (8.1761 m)
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	Default (16.352 m)
Mesh Defeaturing	Yes
Defeature Size	3.e-002 m
Capture Curvature	Yes
Curvature Min Size	6.e-002 m
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	163.52 m
Average Surface Area	40.688 m²
Minimum Edge Length	0.23562 m
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	0.9
Smoothing	Medium
Mesh Metric	None
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	1031769
Elements	5561358

Input parameters:	
Min Size (m)	0.03
Max Size (m)	0.06
Average of Skewness	0.90
Output results:	
Number of Nodes	1,031,769
Number of Elements	5,561,358

After the setting up, meshes have been generated for the Model 2 and presented in the below figures.

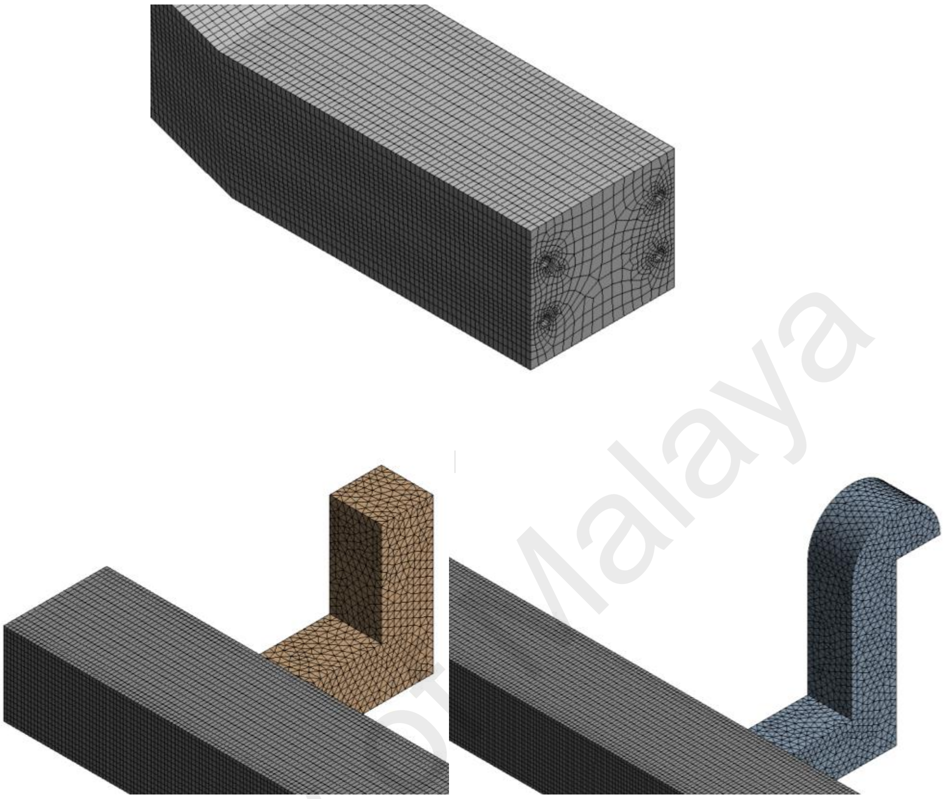


Figure 32: Generated Meshes for Model 2

3.5.3 Step 3 – Setup Model of Computation

In this section, both model will be compute under steady state heat transfer condition but not transient condition. Besides that, only two computation models will be use in the simulations which are (i) Energy and (ii) Viscous, while the rest are remain off.

In Viscous Model, K-epsilon (2eqn) has been selected and the k-epsilon Model to be changed into “Realizable” mode. While the Near-Wall Treatment to be set to “Scalable Wall Function”.

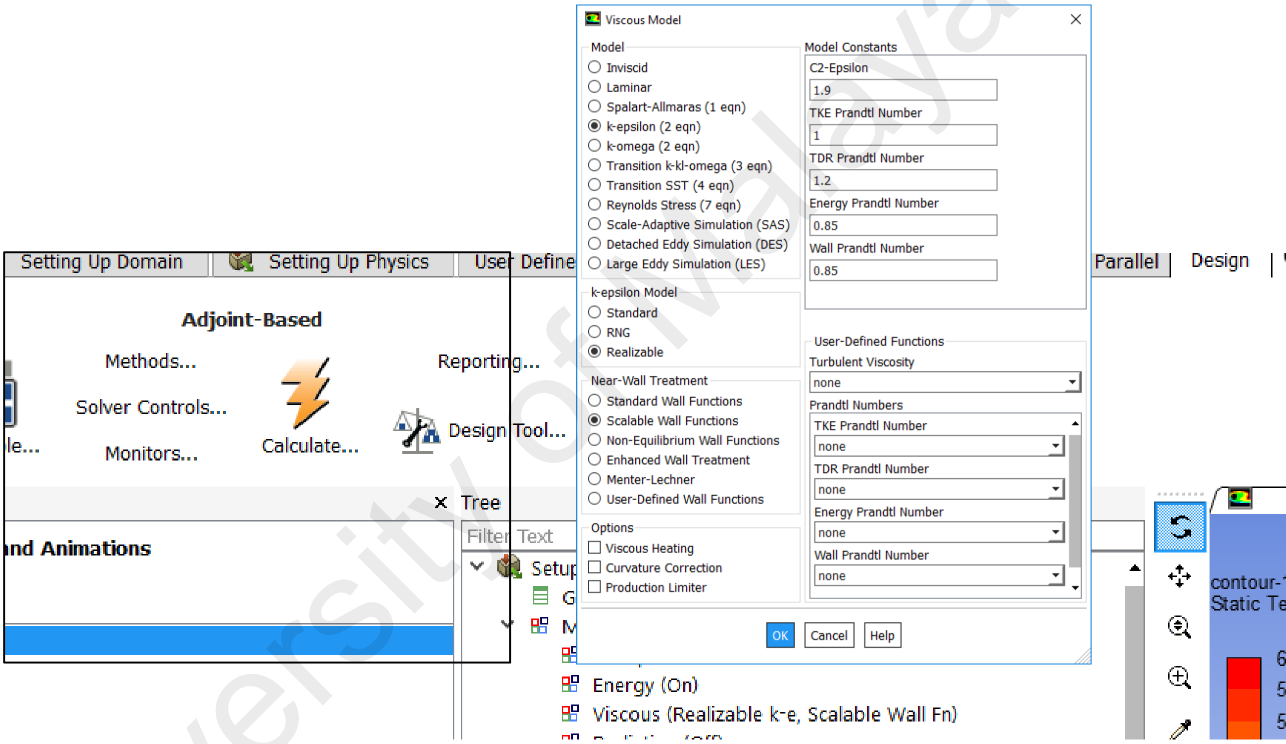


Figure 33: Setup Model of computation for Model 1 & 2

3.5.4 Step 4 – Setup Boundary Conditions

In order to determine the best air flow rate and the best ventilation system for the underground cable tunnel, there are two sets of manipulative variables need to be analyzed which are (i) Input air temperature and (ii) Air change rate (ACH). Overall, 8 simulations with different variables need to be conducted and the 8 respective output results need to be analyzed.

Table 9: Setup of Boundary Conditions for Model 1 & 2

<table>
<tr><th>Description</th><th>Input Air Temperature (°C)</th><th>ACH</th><th>Tunnel Volume (m^3)</th><th>Air flow rate (m^3/h)</th><th>Each Supply Air Inlet Area (m^2)</th><th>No of Supply Air Inlet</th><th>Supply Air Velocity at Inlet (m/s)</th></tr>
<tr><td rowspan="4"><u>Model 1</u>
Longitudinal Ventilation</td><td rowspan="2">33.63</td><td>10</td><td rowspan="8">1173.6</td><td>11736</td><td rowspan="4">7.2</td><td rowspan="4">1</td><td>0.4527</td></tr>
<tr><td>20</td><td>23472</td><td>0.9055</td></tr>
<tr><td rowspan="2">37.00</td><td>10</td><td>11736</td><td>0.4527</td></tr>
<tr><td>20</td><td>23472</td><td>0.9055</td></tr>
<tr><td rowspan="4"><u>Model 2</u>
Semi-Transverse Ventilation</td><td rowspan="2">33.63</td><td>10</td><td>11736</td><td rowspan="4">1</td><td rowspan="4">3</td><td>1.0867</td></tr>
<tr><td>20</td><td>23472</td><td>2.1733</td></tr>
<tr><td rowspan="2">37.00</td><td>10</td><td>11736</td><td>1.0867</td></tr>
<tr><td>20</td><td>23472</td><td>2.1733</td></tr>
<tr><td colspan="8">Fixed Parameters:</td></tr>
<tr><td>Cable Surface Temperature</td><td colspan="7">60°C</td></tr>
</table>

3.5.5 Step 5 – Initialization Computation

Once Step 1 – 4 were set, hit the “Run Calculation” button and key in the number of iteration and it is good to go. The number of iteration for all the simulations in this research to be initialize with 600 iterations.

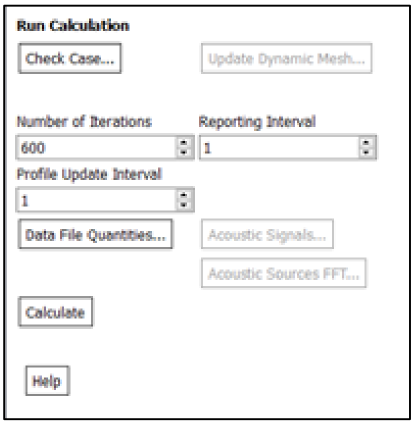


Figure 34: Setup of Number of Iterations

CHAPTER 4: RESULTS & DISCUSSION

4.1 Simulation Results for Model 1 - Longitudinal ventilated underground cable tunnel

A total of 4 numbers CFD simulations have been done under Model 1 – Longitudinal ventilated underground cable tunnel. 4 different combination of variables have been simulated on this model which are presented as follows:

1. 10 air change per hour (ACH) with average ambient temperature 33.63°C
2. 10 air change per hour (ACH) with critical ambient temperature 37.00°C
3. 20 air change per hour (ACH) with average ambient temperature 33.63°C
4. 20 air change per hour (ACH) with critical ambient temperature 37.00°C

The cable tunnel internal temperature at 3 position will be analyze. The position of 3 cross section areas as shown below:

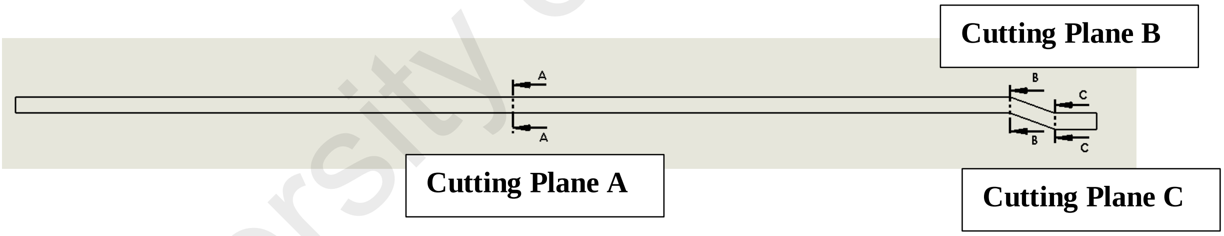


Figure 35: Position of the cut-sections for results

The critical point to be analyze at cross section area will be the midpoint temperature of the cable tunnel. This is to ensure that the cable tunnel internal temperature remain below the criteria of maximum internal temperature of 40°C.

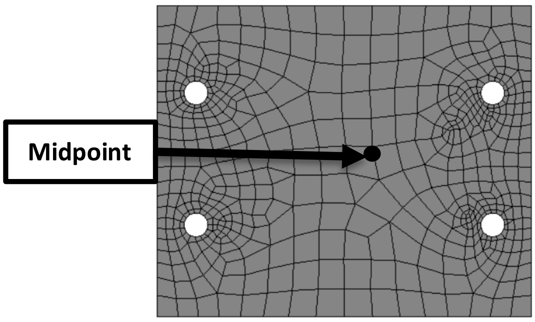


Figure 36: Midpoint Temperature

4.1.1 Model 1 - 10 Air Change Per Hour (ACH) with Average Ambient Temperature 33.63°C

The result converged at iteration no. 486.

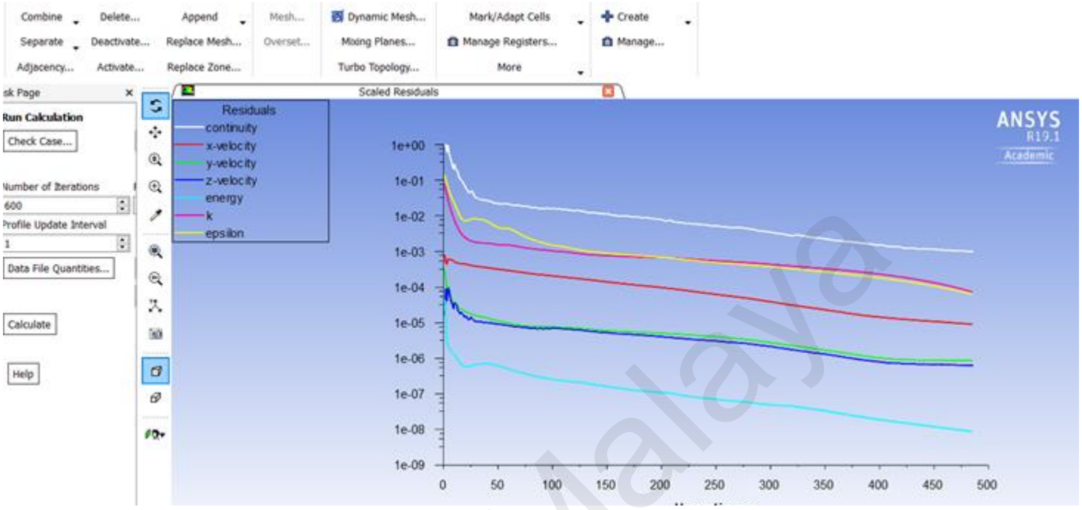


Figure 37: Model 1 - Convergence Graph @ 10ACH @ 33.63°C

Ambient Temperature (°C)	33.63 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area (m^2)	7.2 m^2
Velocity of Intake Air (m/s)	0.4527 m/s
Air Flow Rate (m^3/h)	11735.28 m^3/h
ACH	10

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	35.854 °C	33.634 °C
Cutting Plane B	37.614 °C	34.210 °C
Cutting Plane C	38.072 °C	34.387 °C
Outlet	38.001 °C	36.090 °C

Temperature Contour at Cross-Section of Tunnel at Plane A;

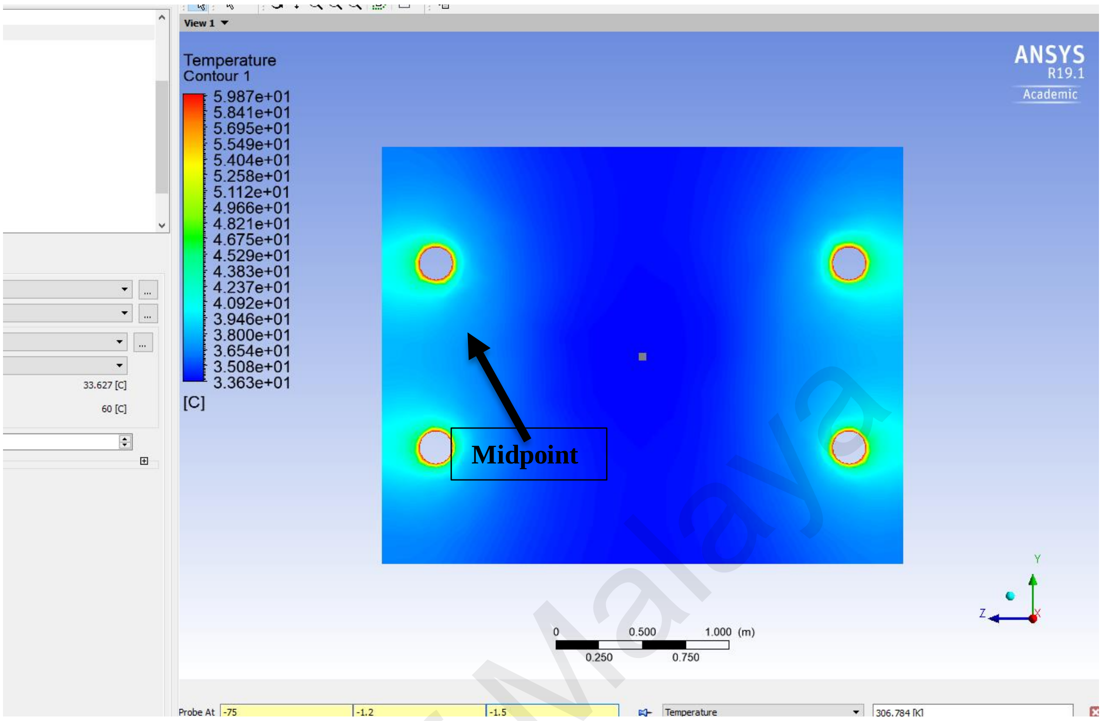


Figure 38: Model 1 - Plane A @ V_i = 0.4527m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane B;

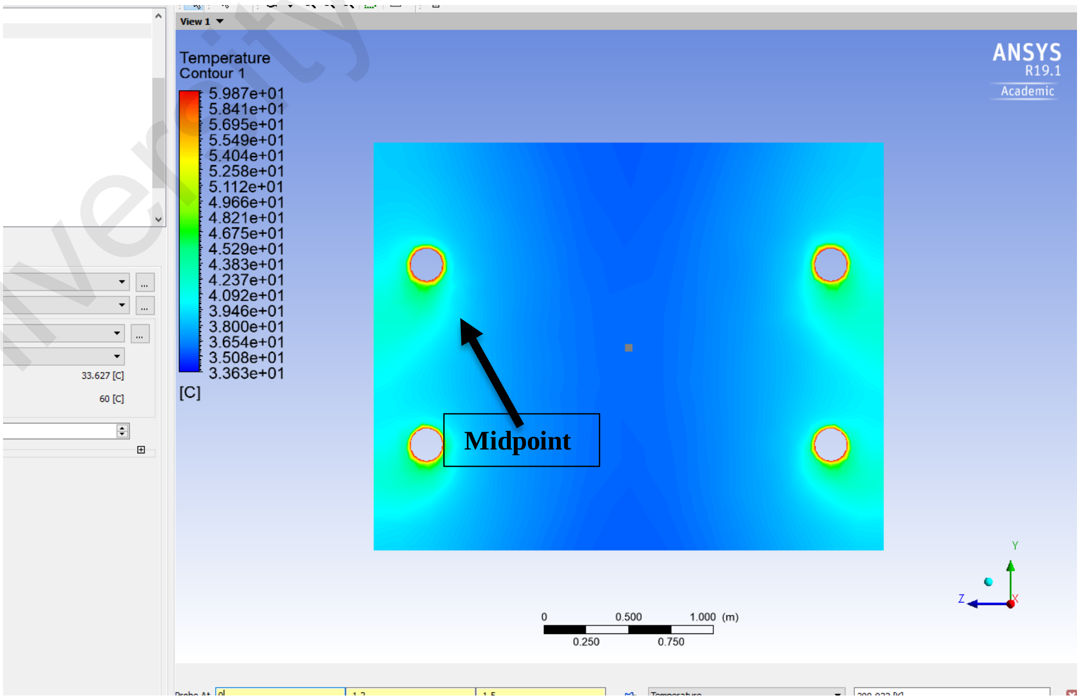


Figure 39: Model 1 - Plane B @ V_i = 0.4527m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane C;

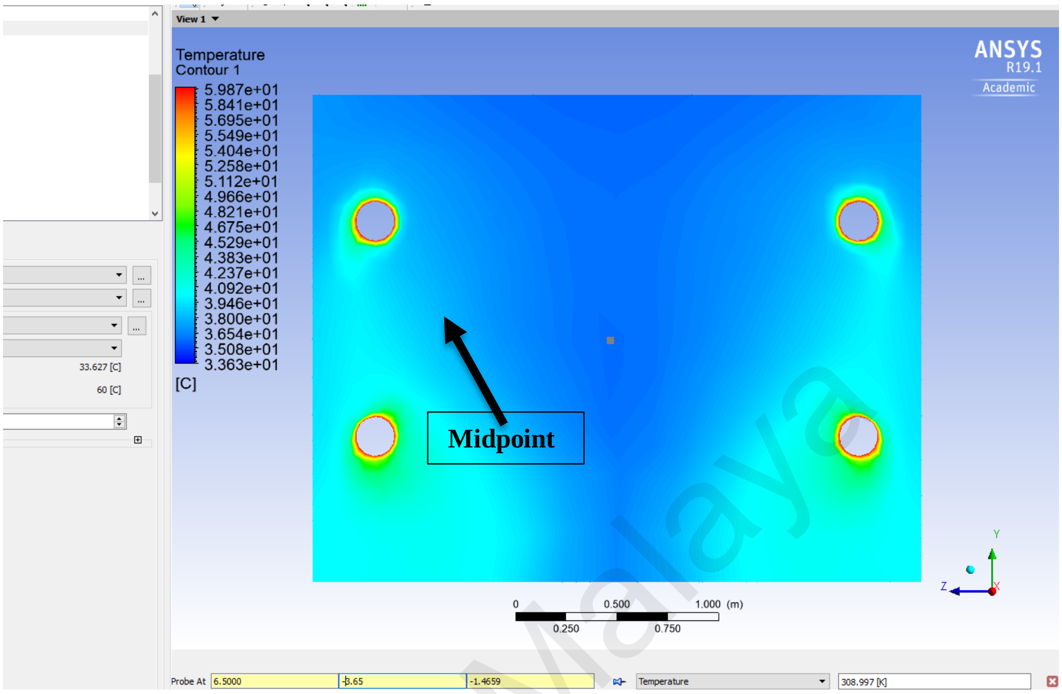


Figure 40: Model 1 - Plane C @ V_i = 0.4527m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Outlet;

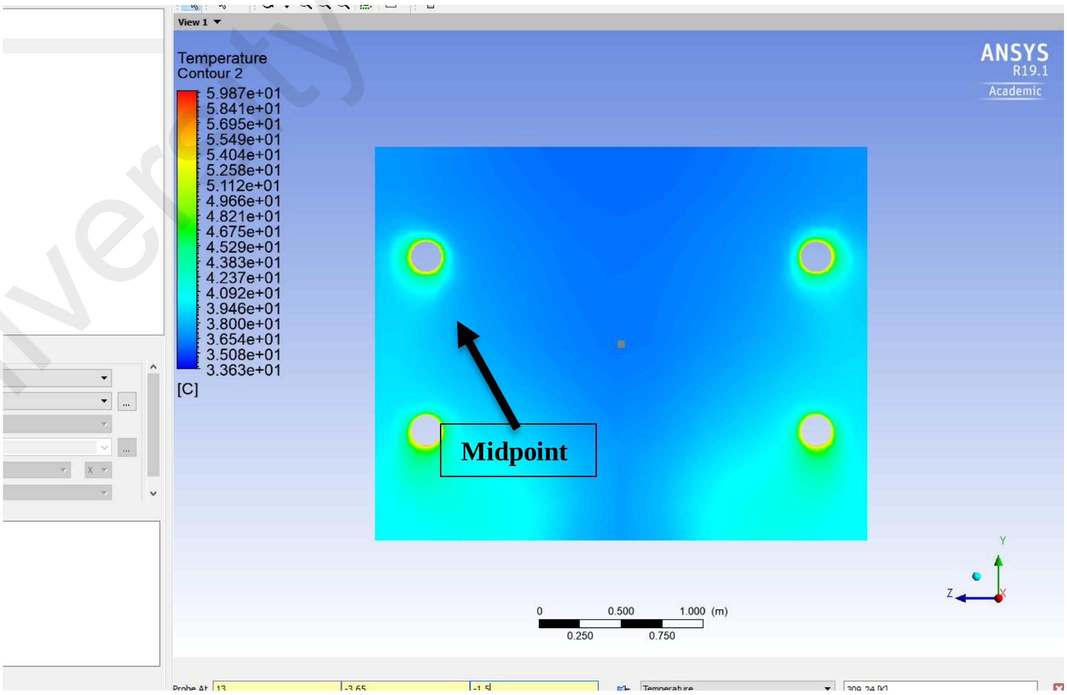


Figure 41: Model 1 - Outlet @ V_i = 0.4527m/s at 33.63°C

4.1.2 Model 1 - 10 Air Change Per Hour (ACH) with Critical Ambient Temperature 37°C

The result converged at iteration no. 498.

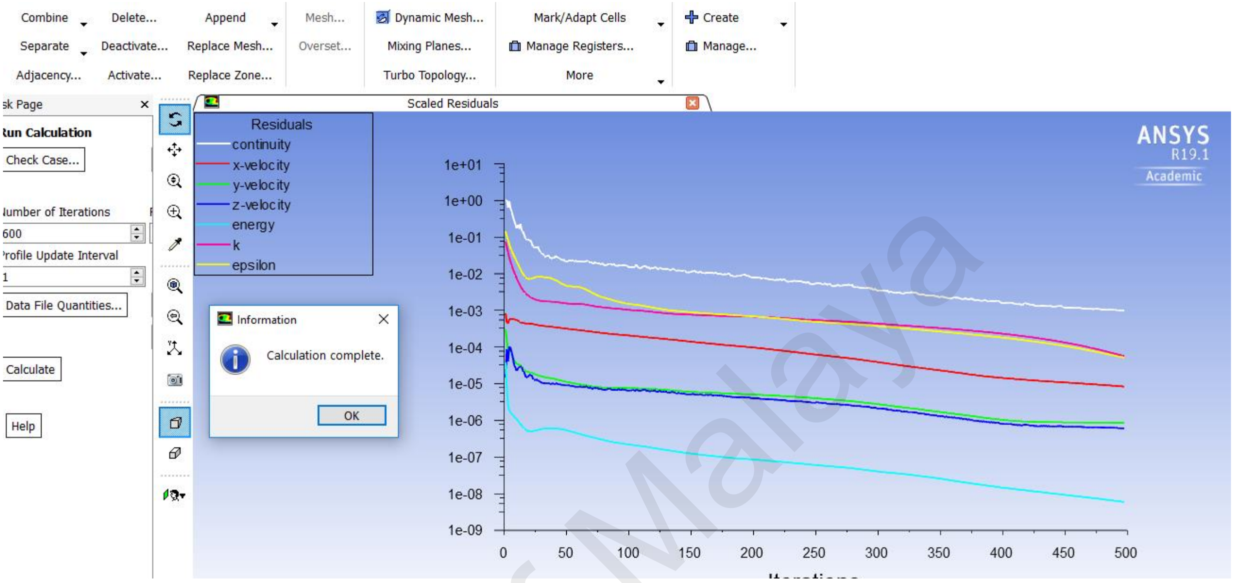


Figure 42: Model 1 - Convergence Graph @ 10ACH @ 37.00°C

Ambient Temperature (°C)	37 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area (m^2)	7.2 m^2
Velocity of Intake Air (m/s)	0.4527 m/s
Air Flow Rate (m^3/h)	11735.28 m^3/h
ACH	10

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	38.940 °C	37.003 °C
Cutting Plane B	40.475 °C	38.891 °C
Cutting Plane C	40.873 °C	38.957 °C
Outlet	40.813 °C	39.156 °C

Temperature Contour at Cross-Section of Tunnel at Plane A;

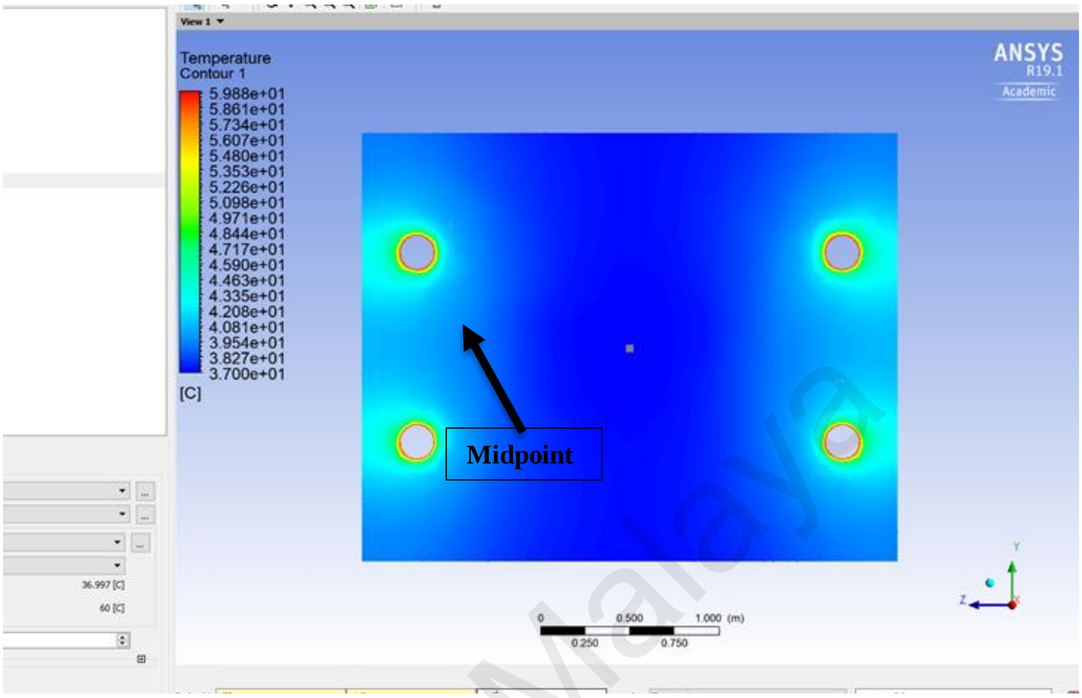


Figure 43: Model 1 - Plane A @ V_i = 0.4527m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane B;

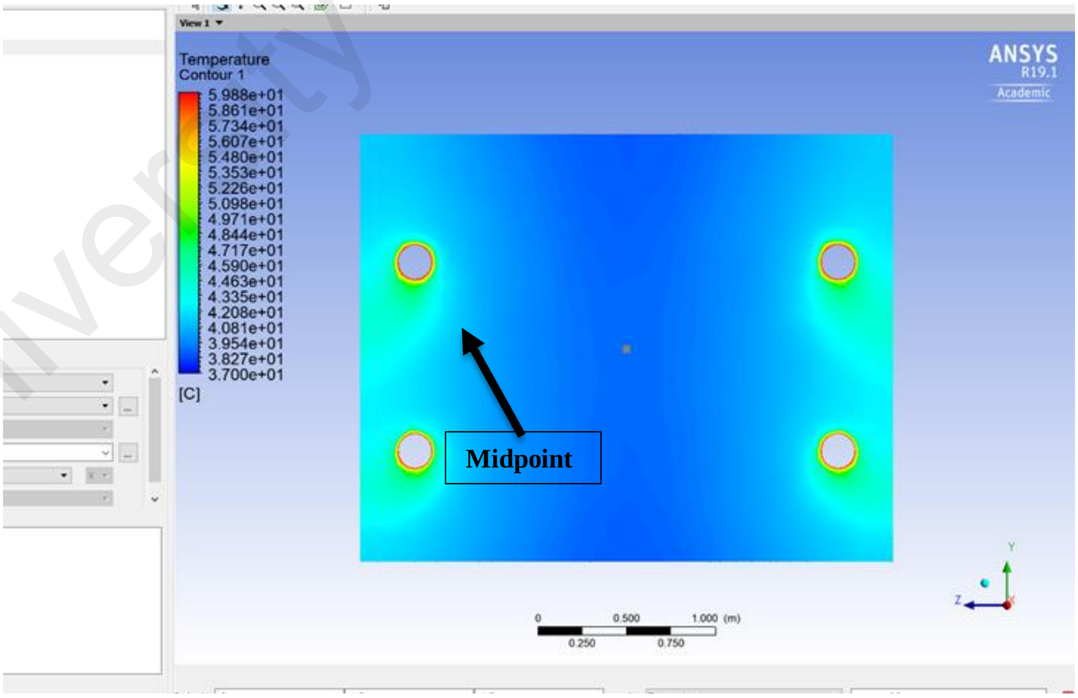


Figure 44: Model 1 - Plane B @ V_i = 0.4527m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane C;

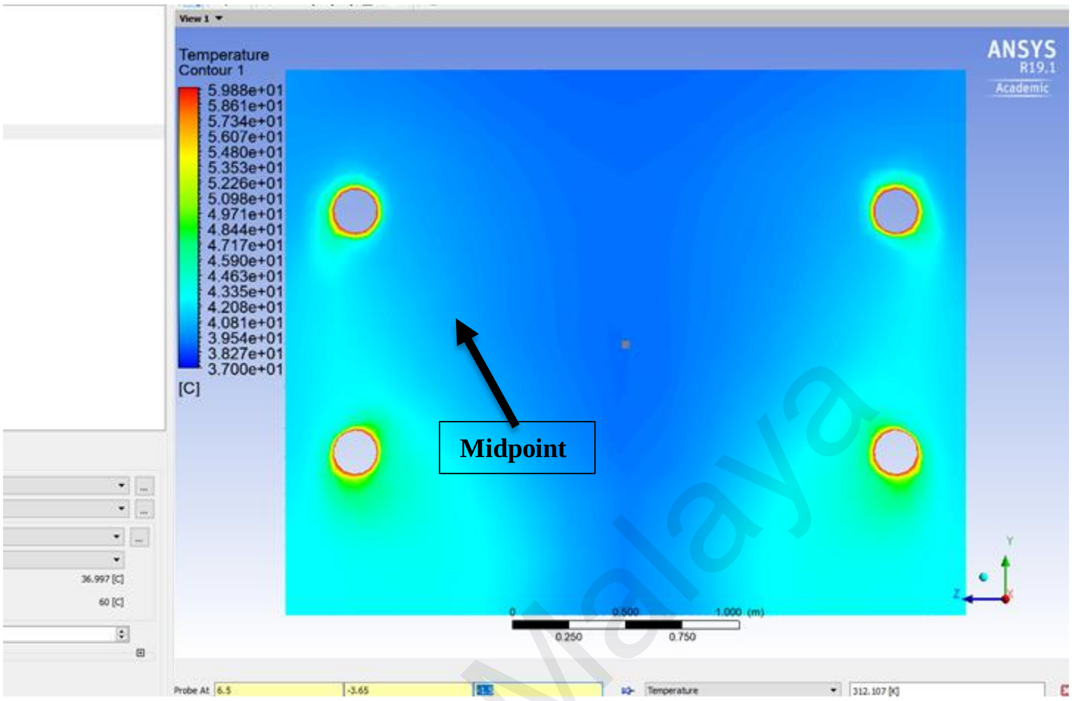


Figure 45: Model 1 - Plane C @ V_i = 0.4527m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Outlet;

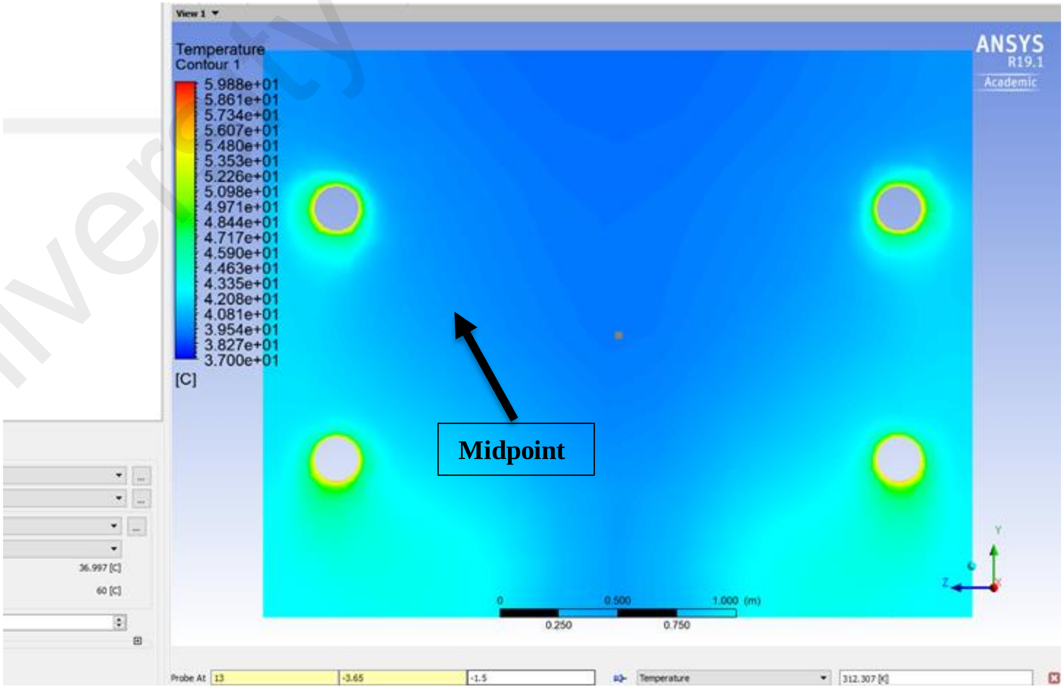


Figure 46: Model 1 - Outlet @ V_i = 0.4527m/s at 37.00°C

4.1.3 Model 1 - 20 Air Change Per Hour (ACH) with Average Ambient Temperature 33.63°C

The result converged at iteration no. 475.

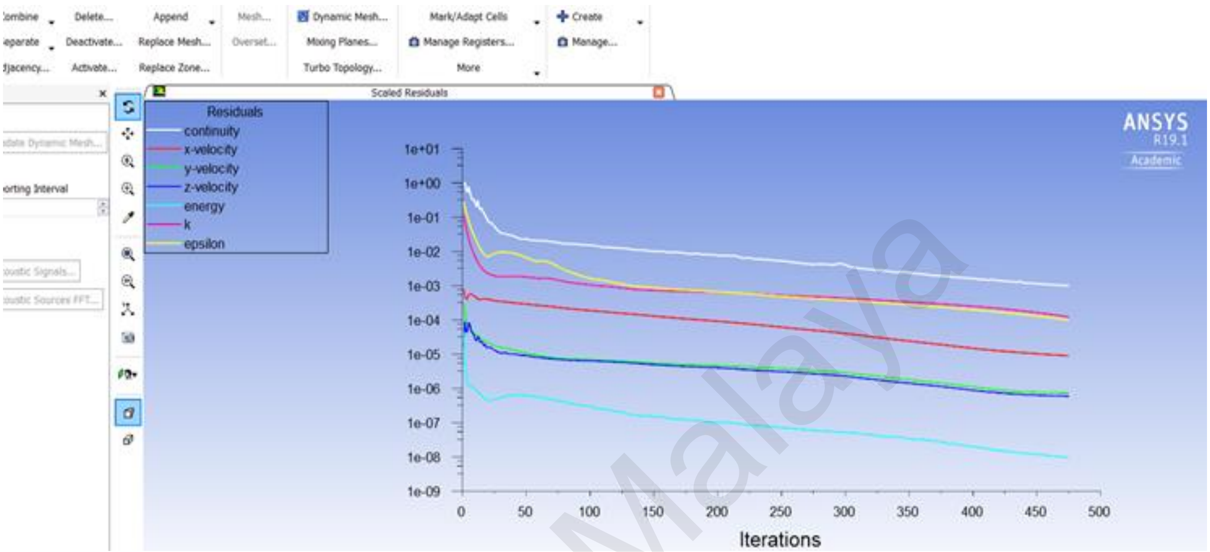


Figure 47: Model 1 - Convergence Graph @ 20ACH @ 33.63°C

Ambient Temperature (°C)	33.63 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area (m^2)	7.2 m^2
Velocity of Intake Air (m/s)	0.9055 m/s
Air Flow Rate (m^3/h)	23470.56 m^3/h
ACH	20

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	35.551 °C	33.630 °C
Cutting Plane B	37.112 °C	35.352 °C
Cutting Plane C	37.453 °C	35.437 °C
Outlet	40.518 °C	35.617 °C

Temperature Contour at Cross-Section of Tunnel at Plane A;

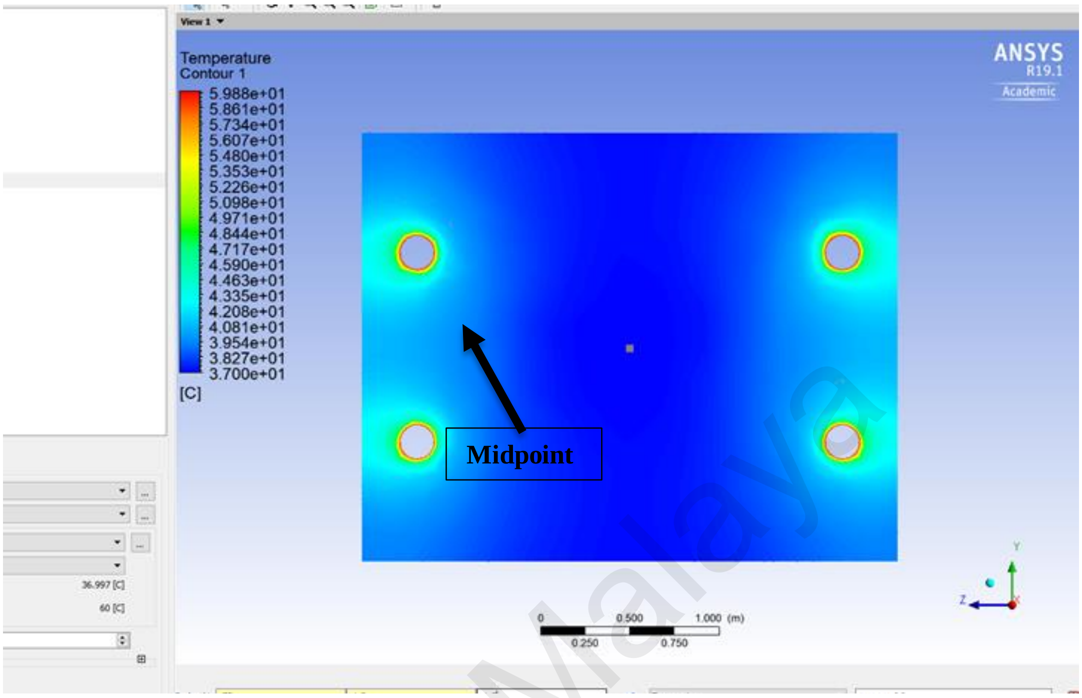


Figure 48: Model 1 - Plane A @ V_i = 0.9055m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane B;

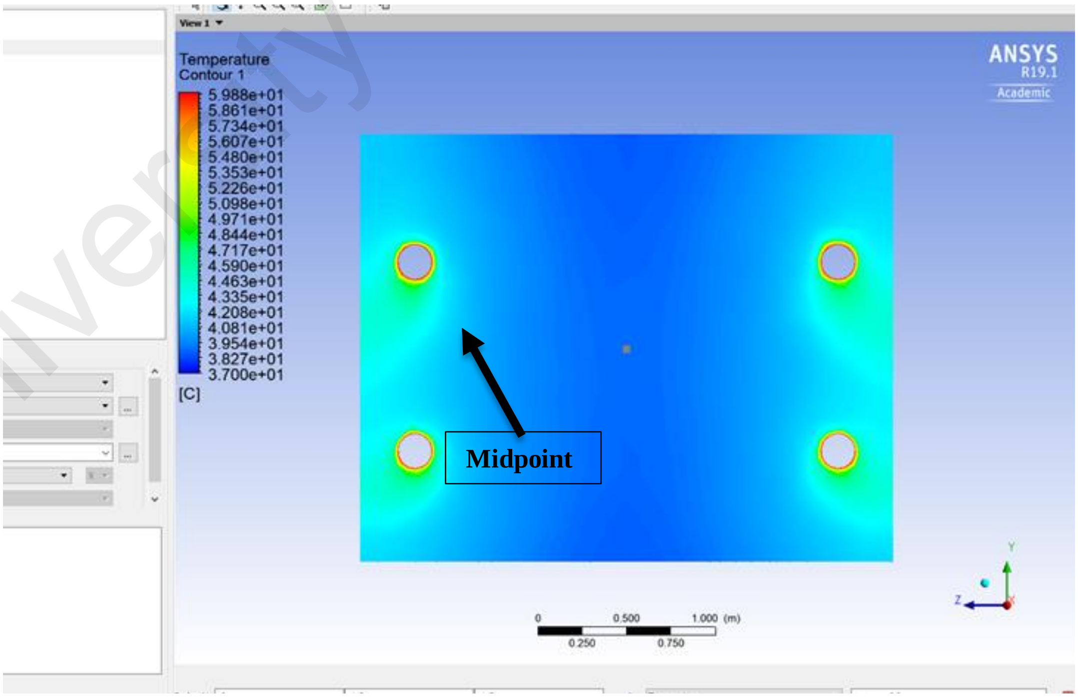


Figure 49: Model 1 - Plane B @ V_i = 0.9055m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane C;

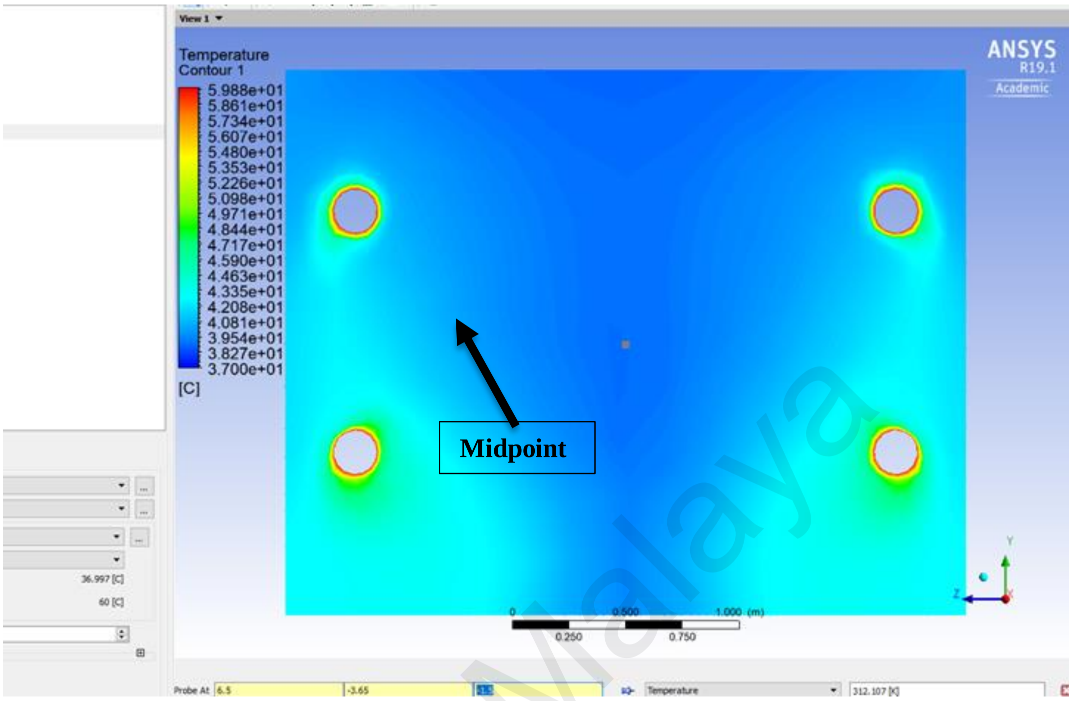


Figure 50: Model 1 - Plane C @ V_i = 0.9055m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Outlet;

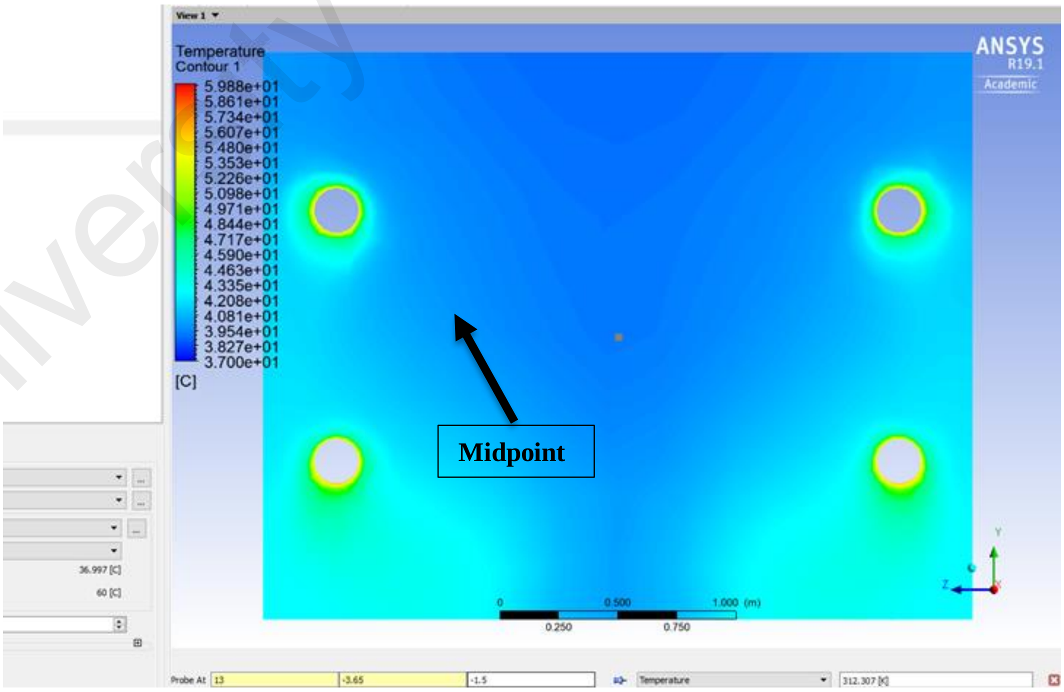


Figure 51: Model 1 - Outlet @ V_i = 0.9055m/s at 33.63°C

4.1.4 Model 1 - 20 Air Change Per Hour (ACH) with Average Ambient Temperature 37.00°C

The result converged at iteration no. 475.

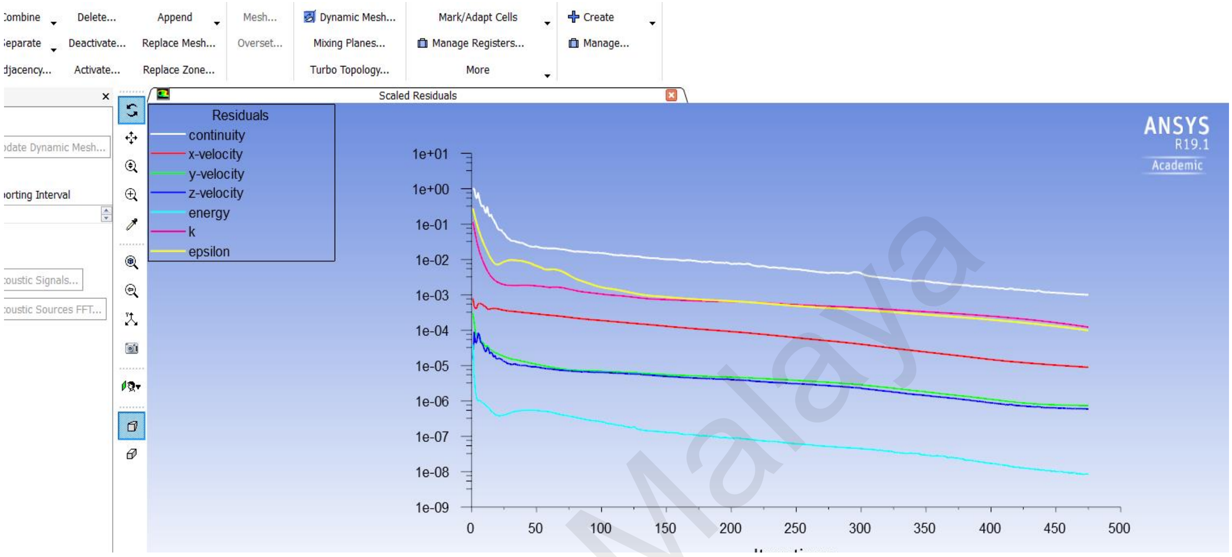


Figure 52: Model 1 - Convergence Graph @ 20ACH @ 37.00°C

Ambient Temperature (°C)	37.00 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area (m^2)	7.2 m^2
Velocity of Intake Air (m/s)	0.9055 m/s
Air Flow Rate (m^3/h)	23470.56 m^3/h
ACH	20

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	38.676 °C	37.000 °C
Cutting Plane B	40.037 °C	38.502 °C
Cutting Plane C	40.391 °C	38.576 °C
Outlet	40.334 °C	38.733 °C

Temperature Contour at Cross-Section of Tunnel at Plane A;

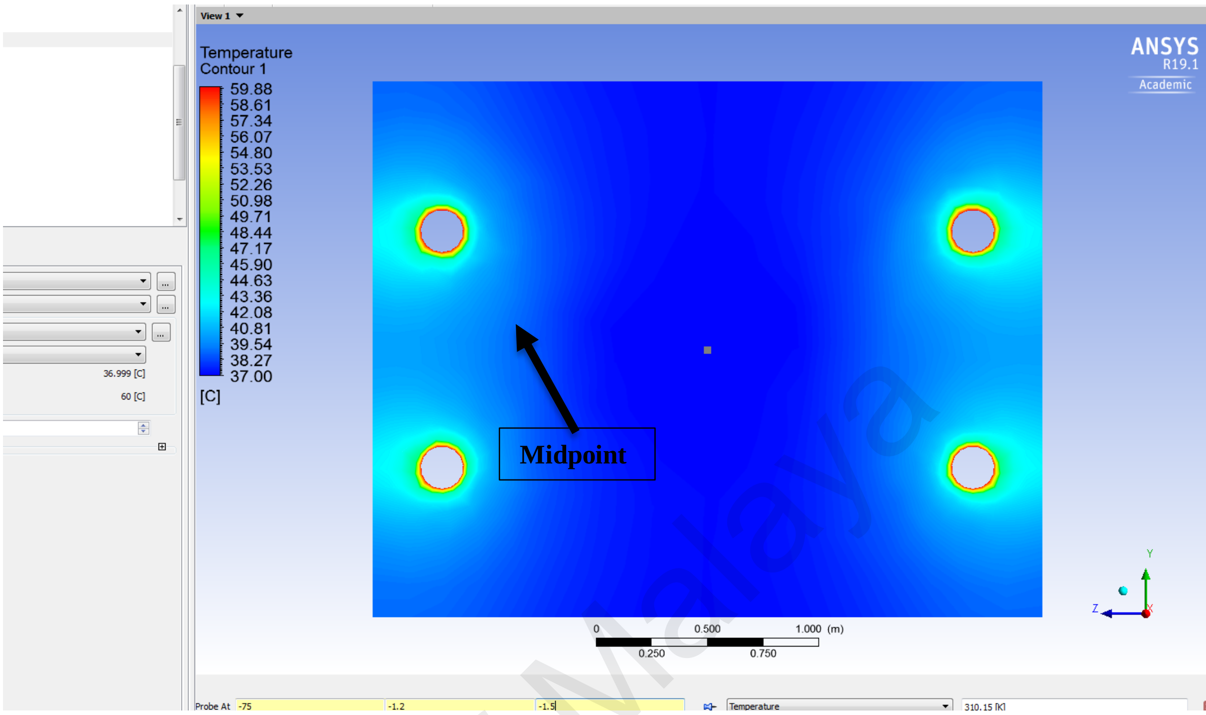


Figure 53: Model 1 - Plane A @ V_i = 0.9055m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane B;

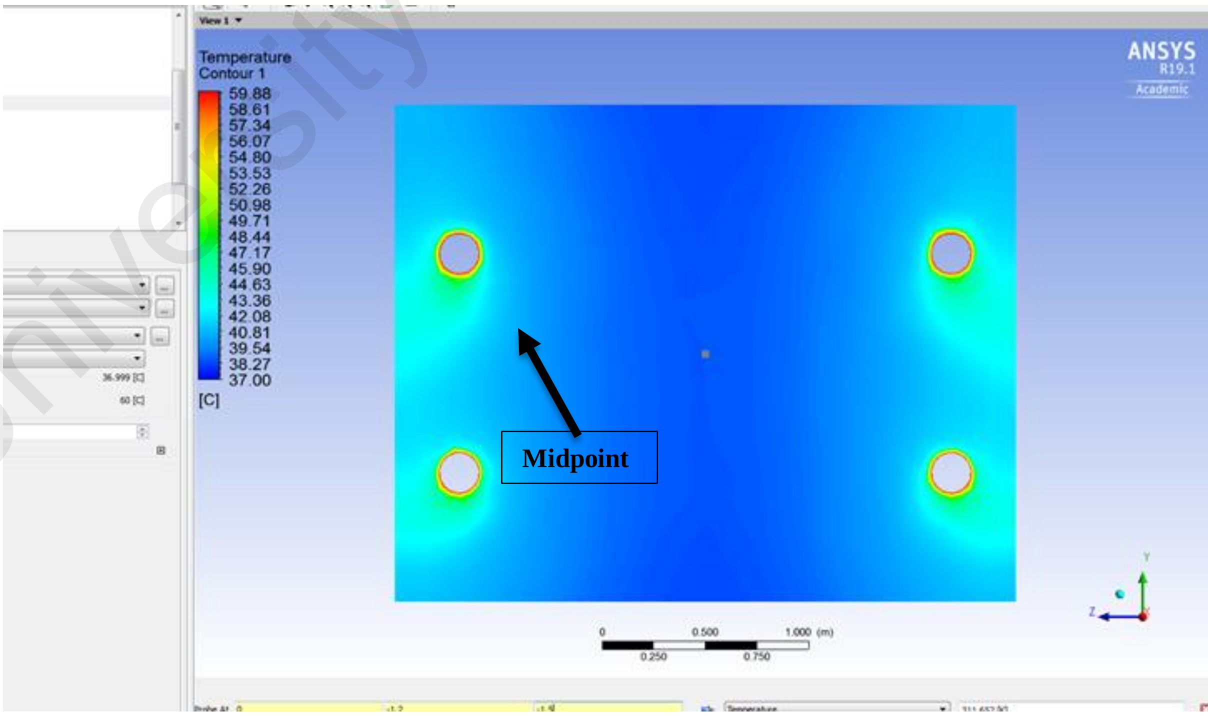


Figure 54: Model 1 - Plane B @ V_i = 0.9055m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane C;

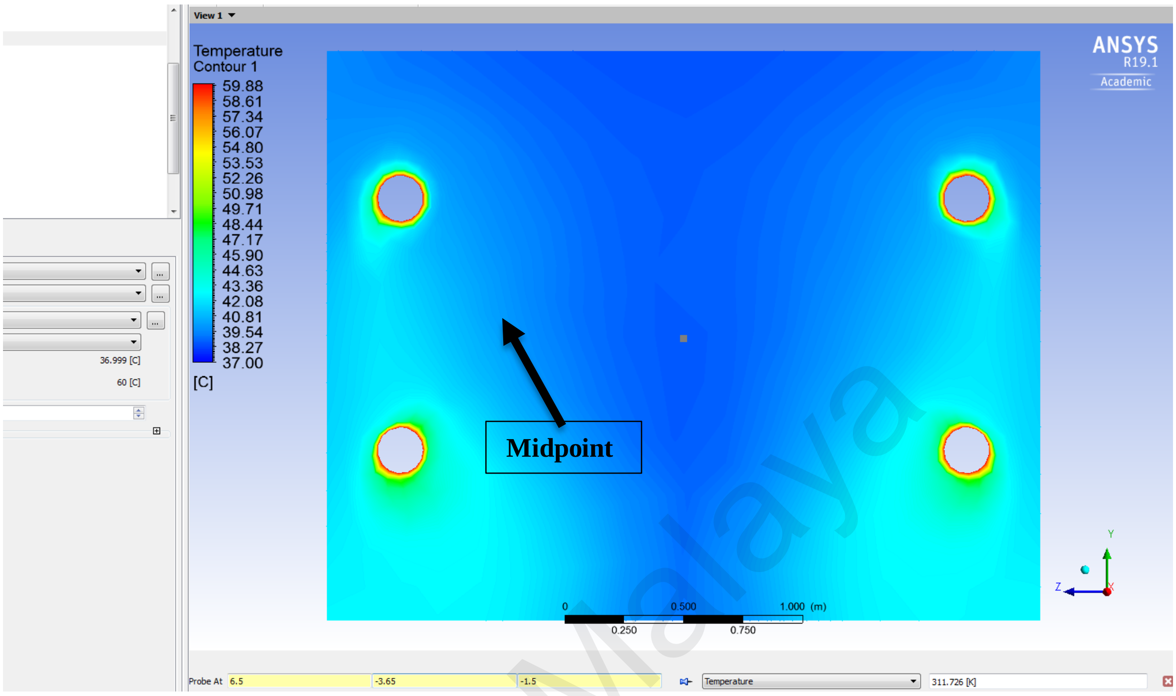


Figure 55: Model 1 - Plane C @ V_i = 0.9055m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Outlet;

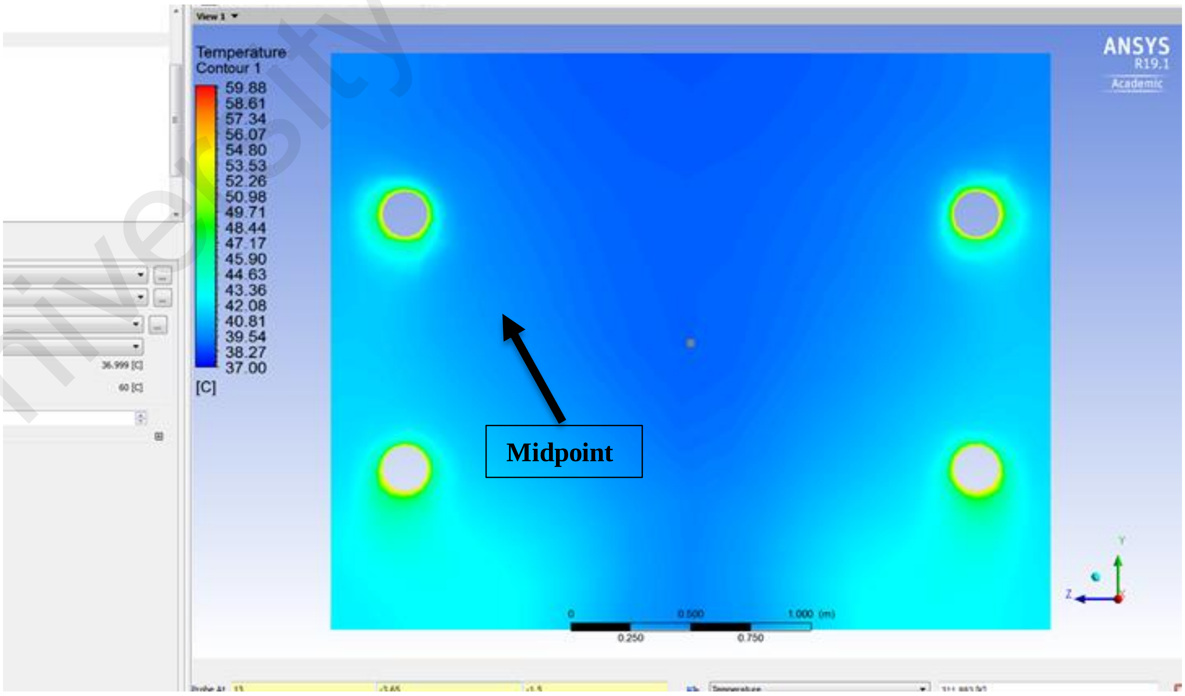


Figure 56: Model 1 - Outlet @ V_i = 0.9055m/s at 37.00°C

4.2 Discussion on Model 1 simulation results

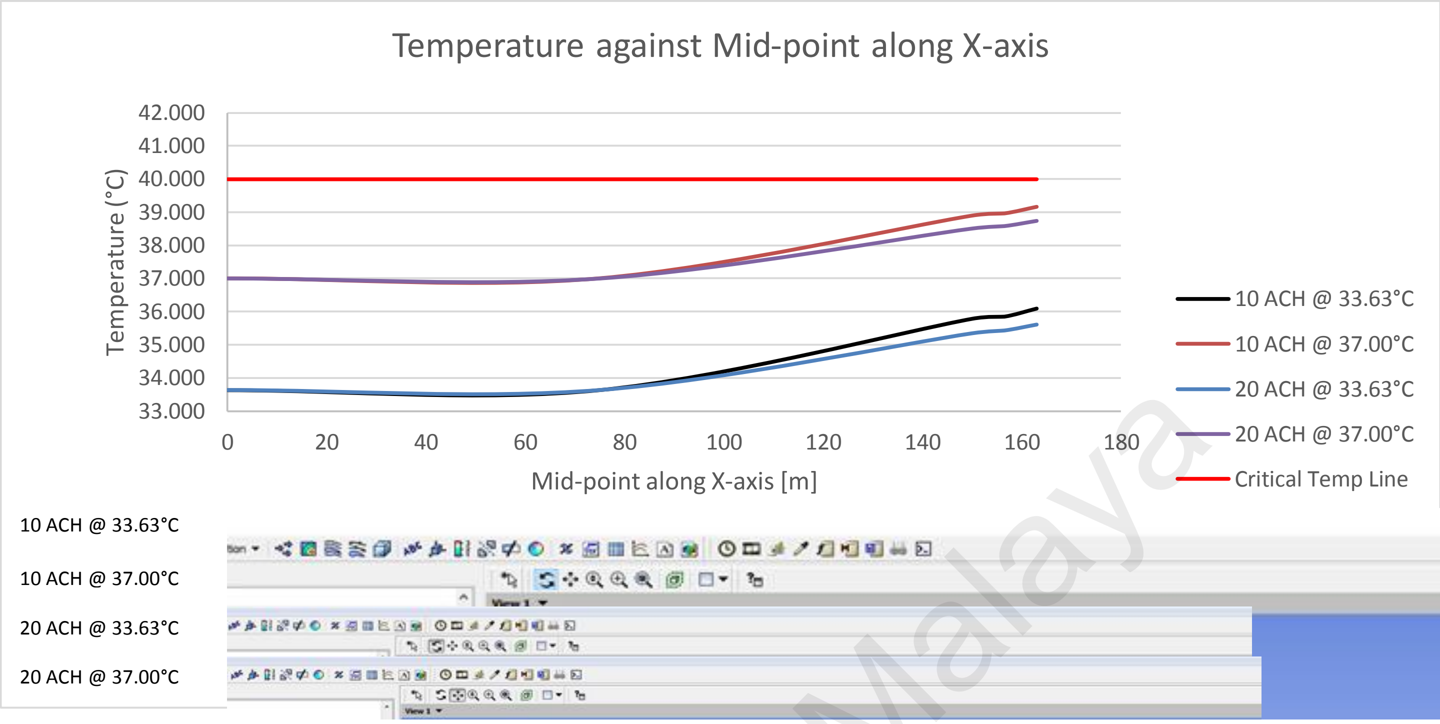
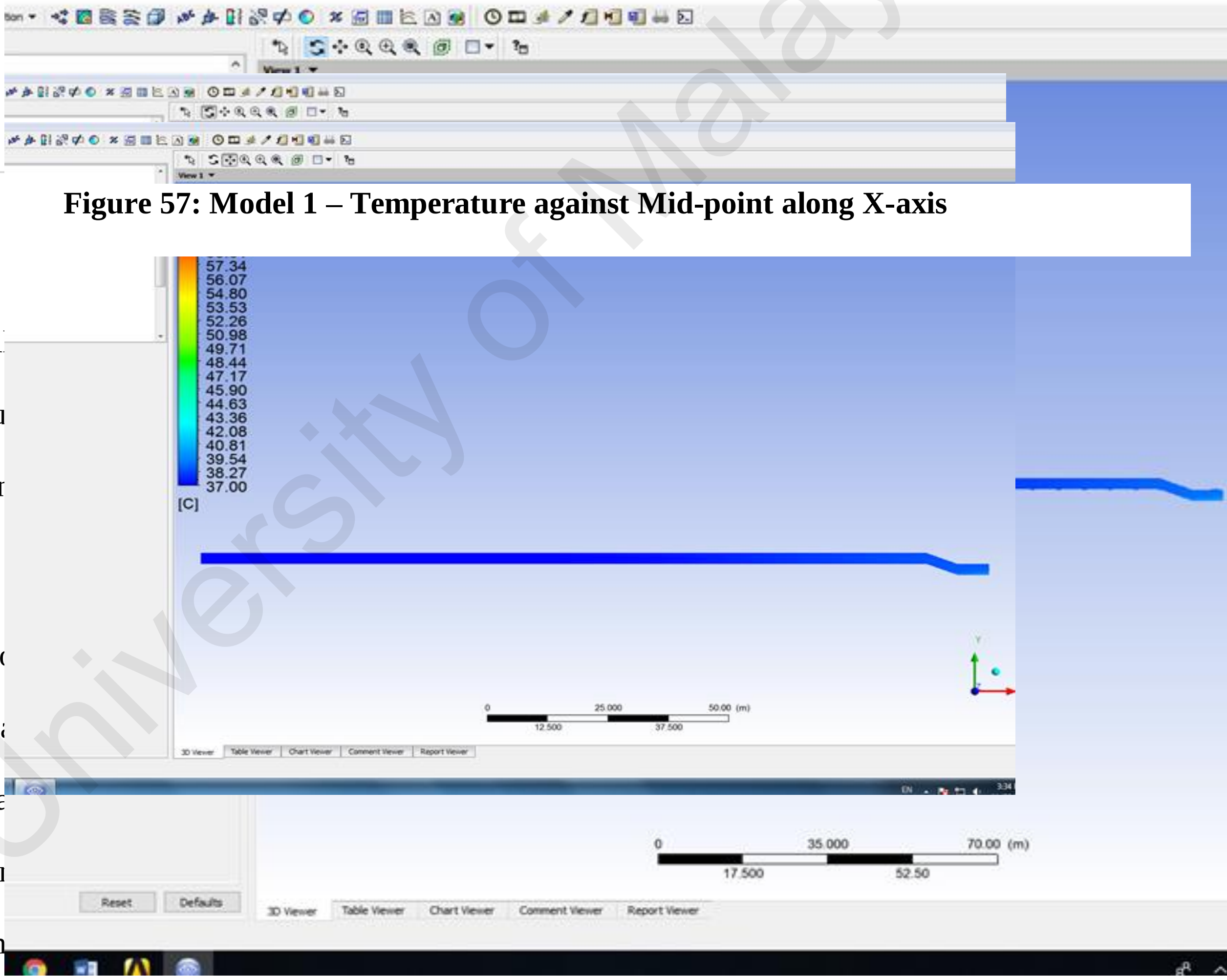


Figure 57: Model 1 – Temperature against Mid-point along X-axis



Al

Tu

tur

In

Mo

hea

tha

can

Th

because the heat will accumulate along the tunnel and the air temperature will be higher at the end part of the tunnel subsequently affect the heat rejection rate of the cable at the end part of the tunnel reduced. Therefore by providing higher ACH, it lowers the internal temperature and the cable derating factor will be lower down. Thus, high voltage cables could have higher current carrying capacity with a lower tunnel internal temperature.

However, if client do have budgetary issues to install a higher air capacity ventilation system, 10ACH can still be used as the middle temperature for entire tunnel still below 40°C. The only disadvantage is that the 132KV cable has a higher derating factor which would lower down the cables current carrying capacity and power transmission.

4.3 Simulation Results for Model 2 - Longitudinal ventilated underground cable tunnel

A total of 4 numbers CFD simulations have been done under Model 2 – Semi Transverse ventilated underground cable tunnel. 4 different combination of variables have been simulated on this model which are presented as follows:

1. 10 air change per hour (ACH) with average ambient temperature 33.63°C
2. 10 air change per hour (ACH) with critical ambient temperature 37.00°C
3. 20 air change per hour (ACH) with average ambient temperature 33.63°C
4. 20 air change per hour (ACH) with critical ambient temperature 37.00°C

The cable tunnel internal temperature at 5 position will be analyze. The position of these 5 cross section areas as shown below:

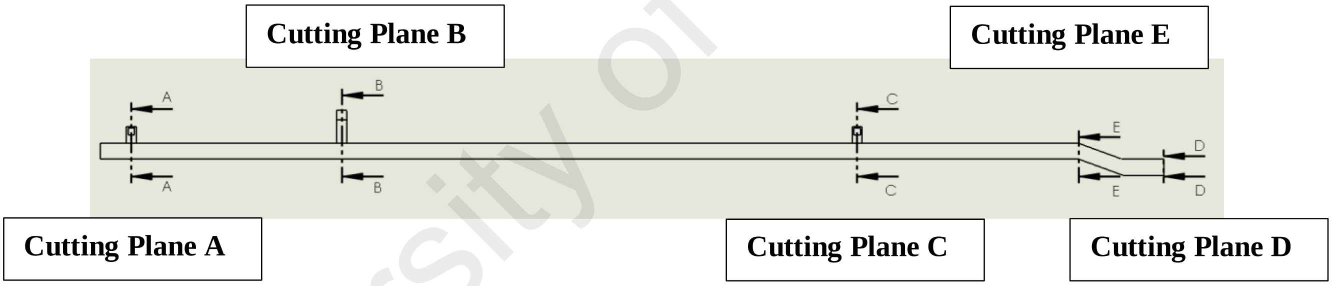


Figure 58: Position of the cut-sections for results

The critical point to be analyze at cross section area will be the midpoint temperature of the cable tunnel. This is to ensure that the cable tunnel internal temperature remain below the criteria of maximum internal temperature of 40°C.

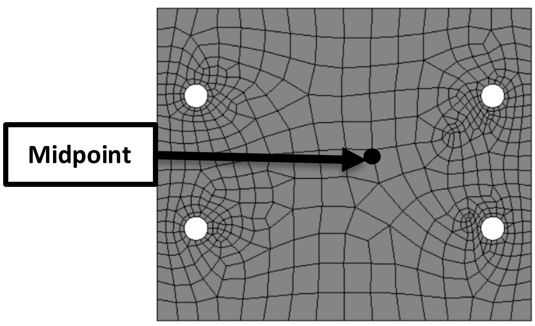


Figure 59: Midpoint Temperature

4.3.1 Model 2 - 10 Air Change Per Hour (ACH) with Average Ambient Temperature 33.63°C

The result did not converged at iteration no. 600.

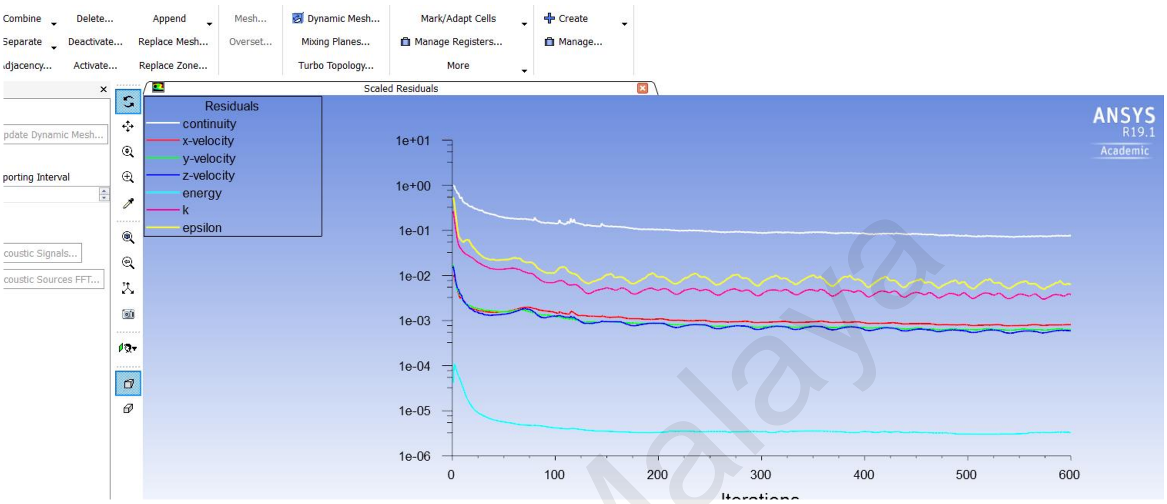


Figure 60: Model 2 - Convergence Graph @ 10ACH @ 33.63°C

Ambient Temperature (°C)	33.63 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area 1 (m^2)	1 m^2
Inlet Area 2 (m^2)	1 m^2
Inlet Area 3 (m^2)	1 m^2
Outlet Area (m^2)	1 m^2
Velocity of Intake Air (m/s)	1.0867 m/s
Total Air Flow Rate (m^3/h)	11736.36 m^3/h
ACH	10

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A (Inlet 1)	33.825 °C	33.700 °C
Cutting Plane B (Outlet)	37.225 °C	38.598 °C
Cutting Plane C (Inlet 2)	34.518 °C	34.478 °C
Cutting Plane D (Inlet 3)	36.136 °C	33.668 °C
Cutting Plane E	35.697 °C	35.553 °C
Outlet	36.803 °C	

Temperature Contour at Cross-Section of Tunnel at Plane A;

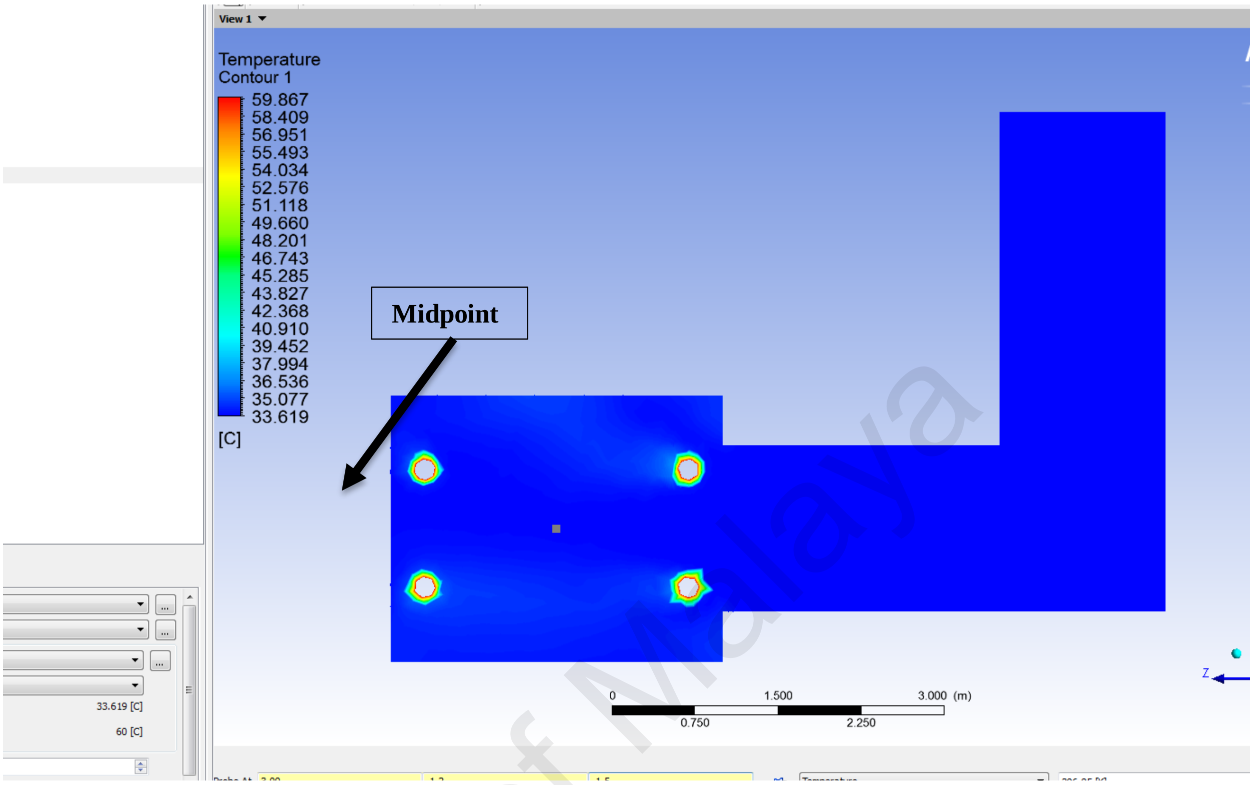


Figure 61: Model 2 - Plane A @ V_i = 1.0867m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane B;

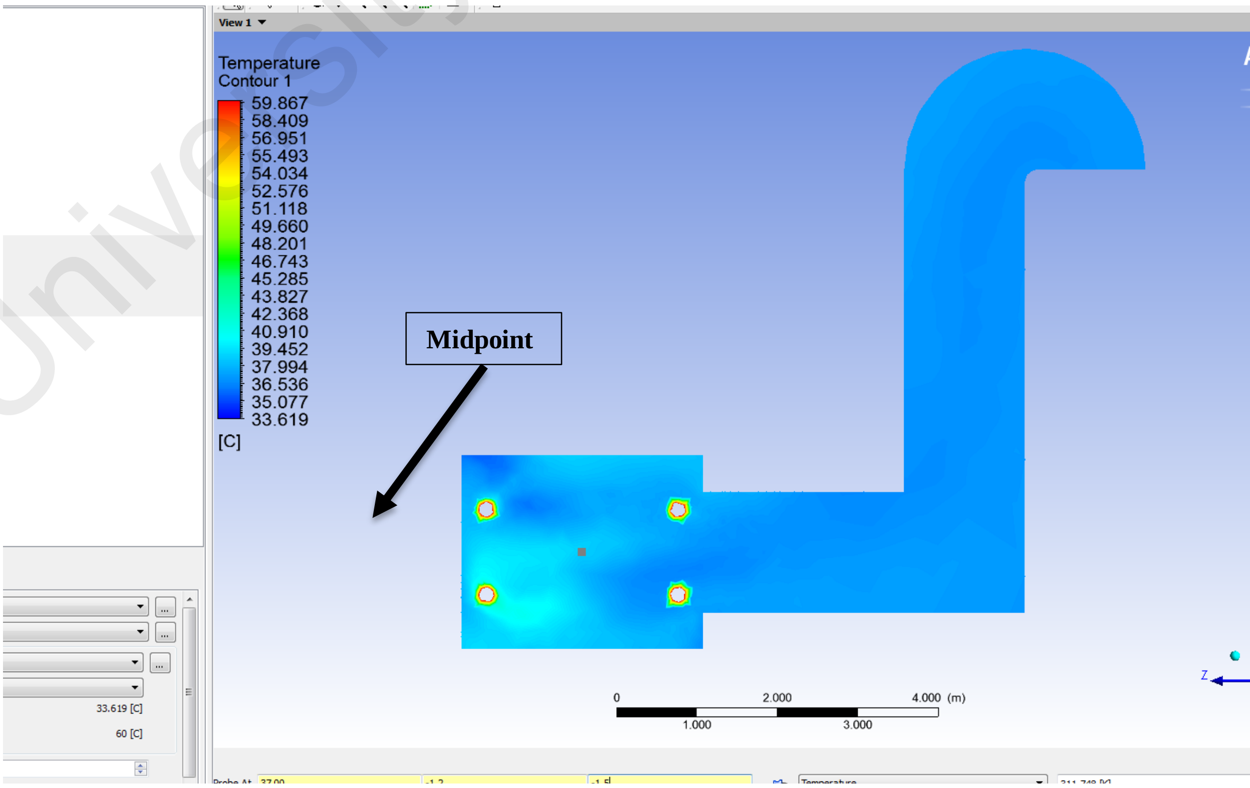


Figure 62: Model 2 - Plane B @ V_i = 1.0867m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane C;

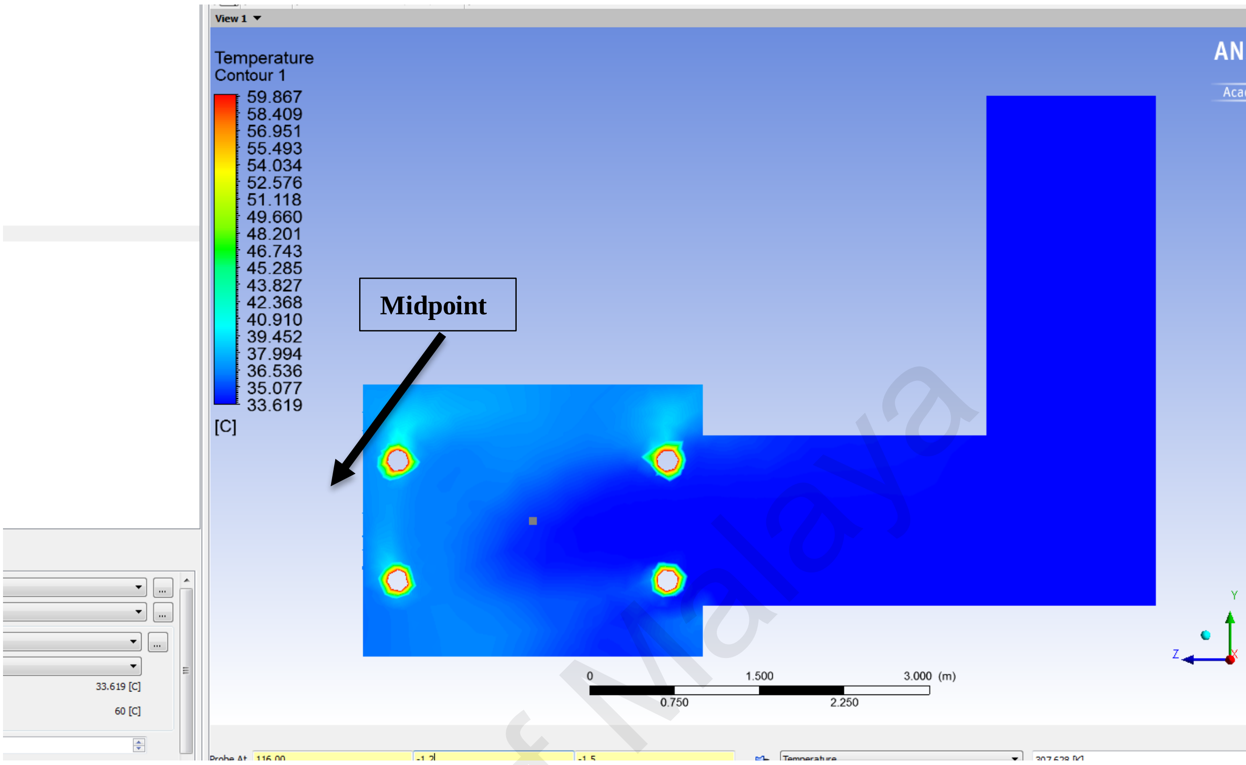


Figure 63: Model 2 - Plane C @ V_i = 1.0867m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane D;

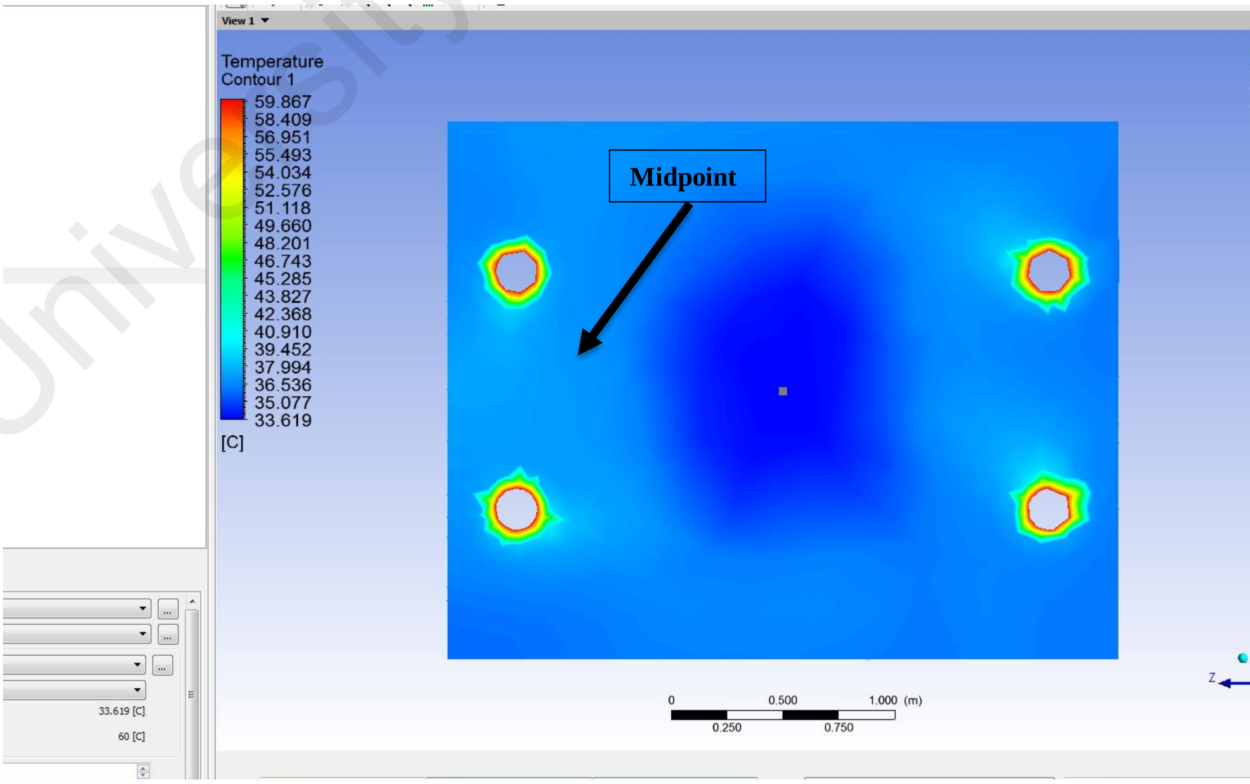


Figure 64: Model 2 - Plane D @ V_i = 1.0867m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane E;

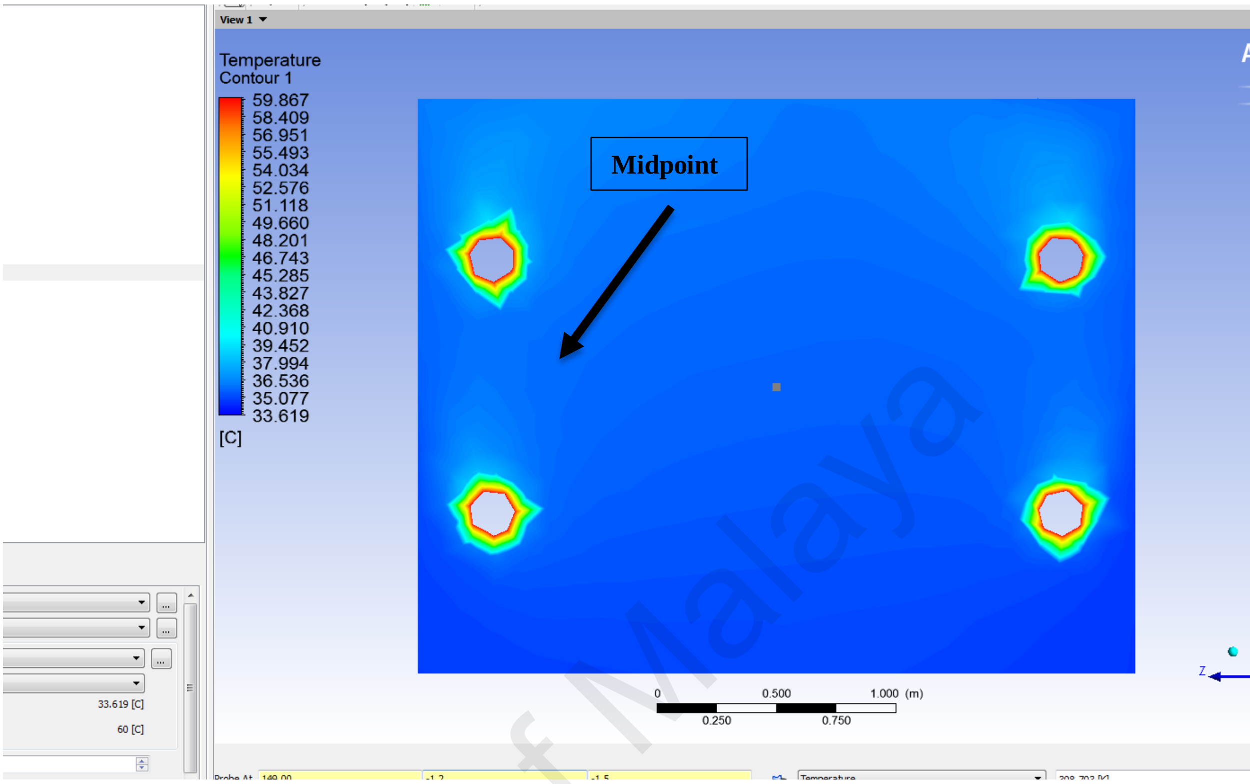


Figure 65: Model 2- Plane E @ V_i = 1.0867m/s at 33.63°C

4.3.2 Model 2 - 10 Air Change Per Hour (ACH) with Average Ambient Temperature 33.63°C

The result did not converged at iteration no. 600.

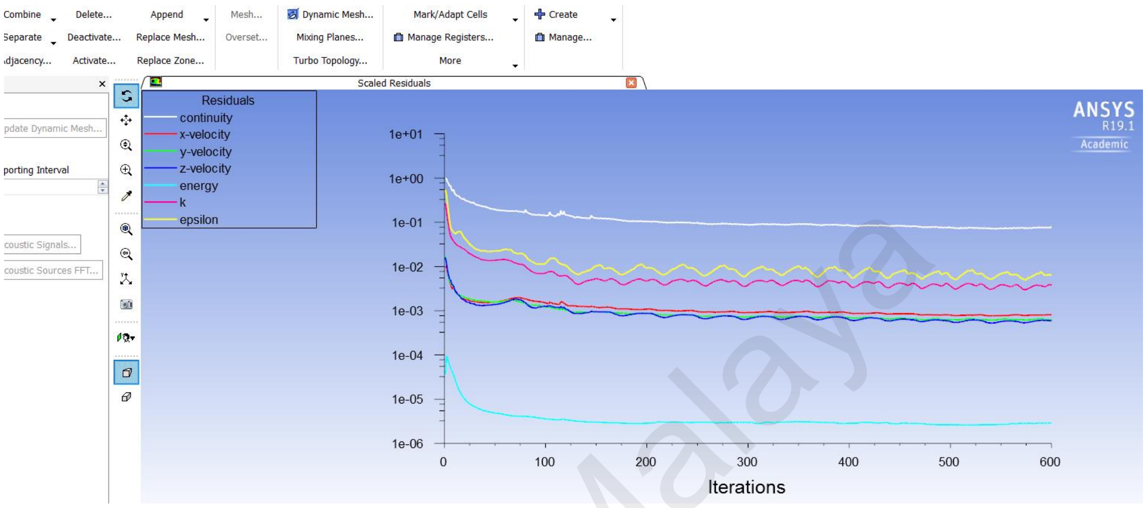


Figure 66: Model 1 - Convergence Graph @ 10ACH @ 37.00°C

Ambient Temperature (°C)	37.00 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area 1 (m^2)	1 m^2
Inlet Area 2 (m^2)	1 m^2
Inlet Area 3 (m^2)	1 m^2
Outlet Area (m^2)	1 m^2
Velocity of Intake Air (m/s)	1.0867 m/s
Total Air Flow Rate (m^3/h)	11736.36 m^3/h
ACH	10

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	37.170 °C	37.061 °C
Cutting Plane B	40.135 °C	41.333 °C
Cutting Plane C	37.774 °C	37.740 °C
Cutting Plane D	39.186 °C	37.034 °C
Cutting Plane E	38.803 °C	38.677 °C
Outlet	39.767 °C	

Temperature Contour at Cross-Section of Tunnel at Plane A;

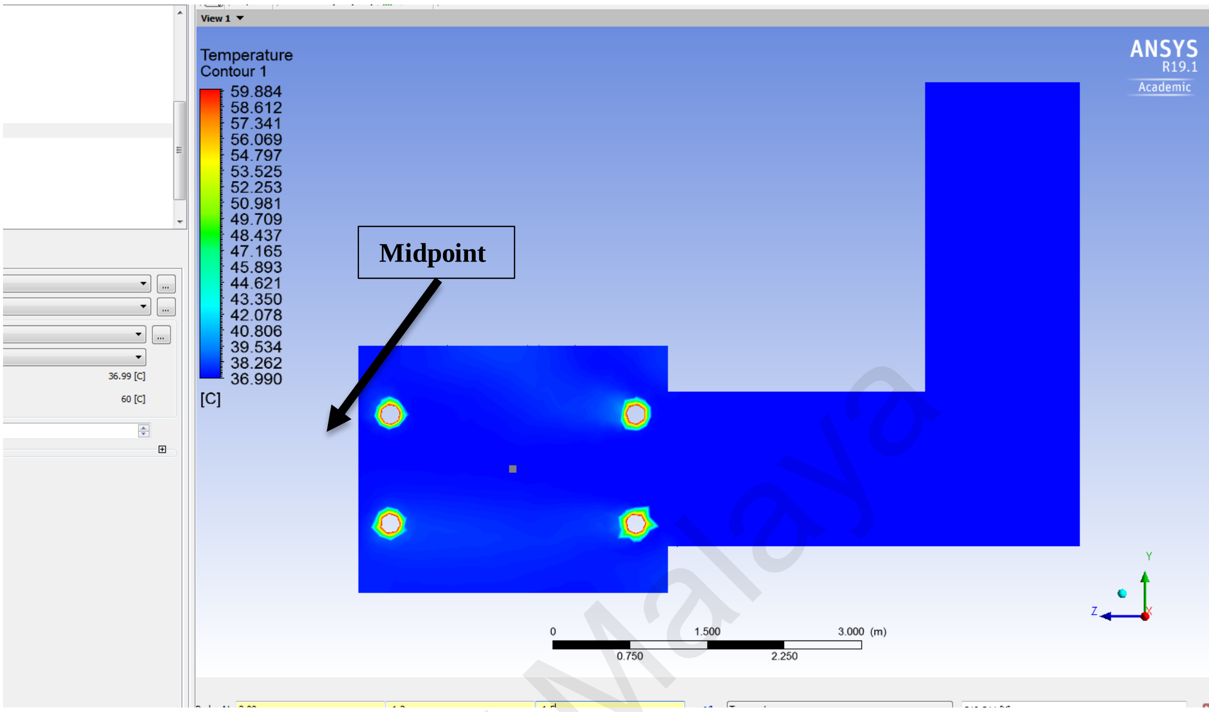


Figure 67: Model 2 - Plane A @ V_i = 1.0867m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane B;

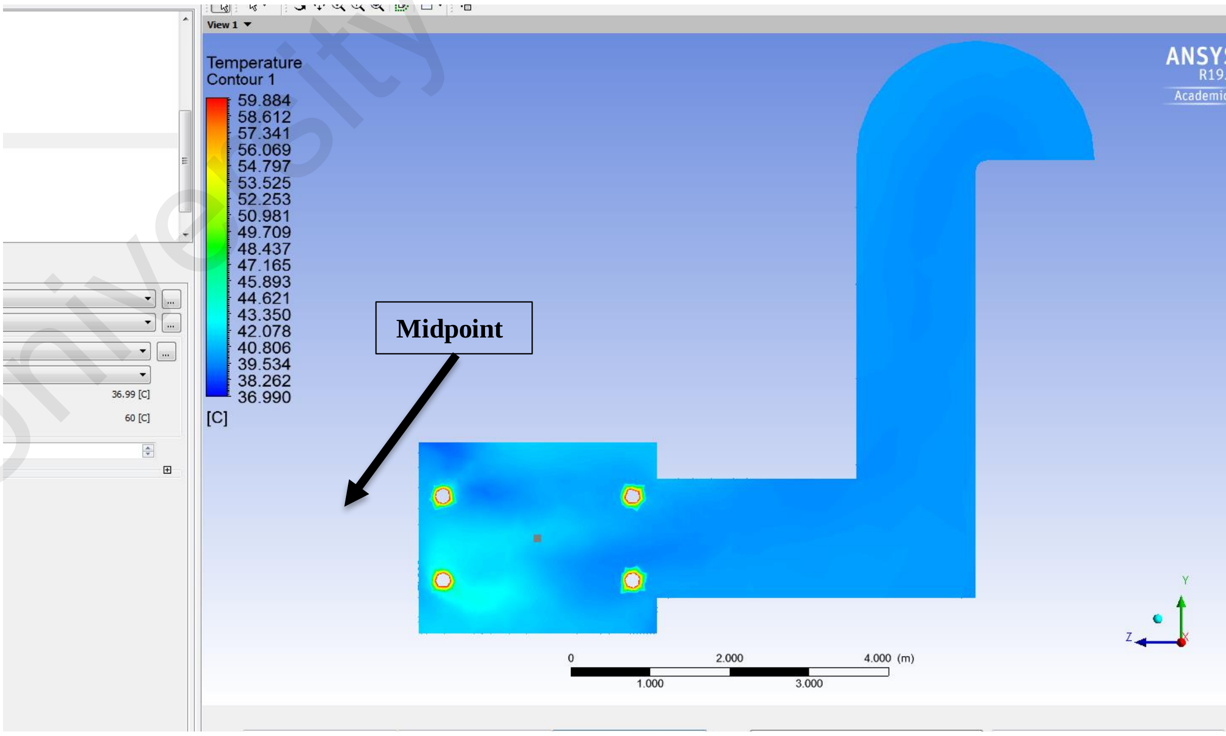


Figure 68: Model 2 - Plane B @ V_i = 1.0867m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane C;

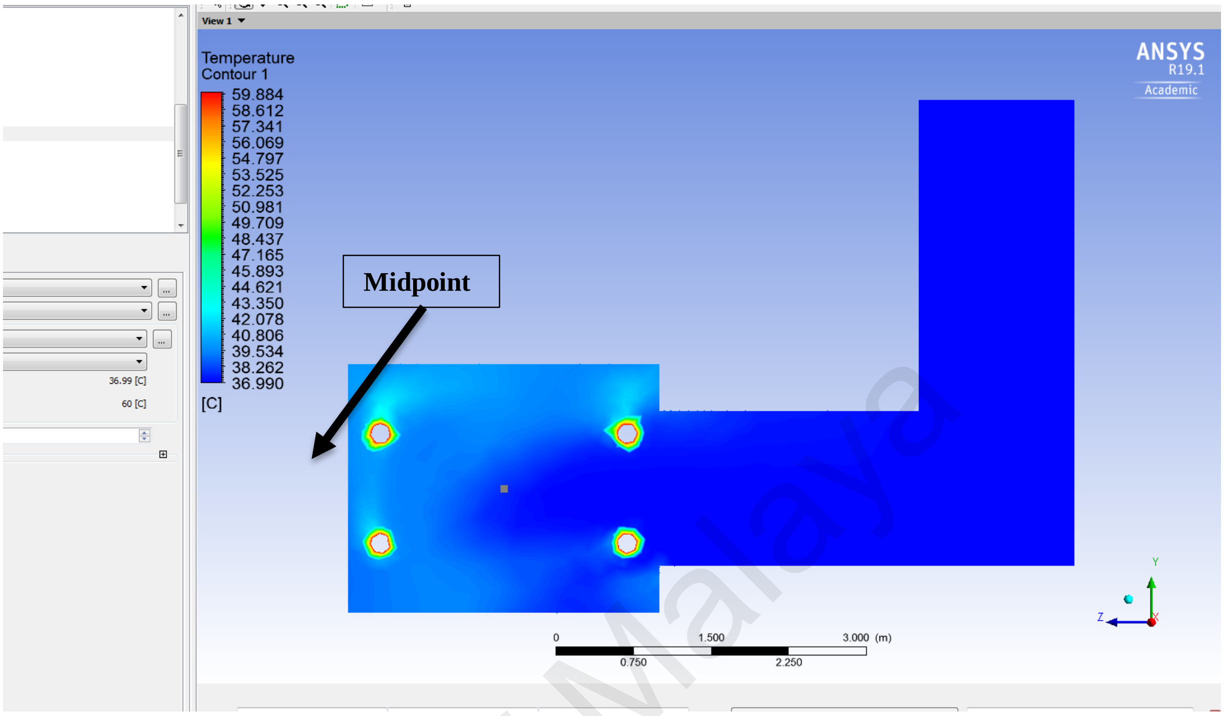


Figure 69: Model 2 - Plane C @ V_i = 1.0867m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane D;

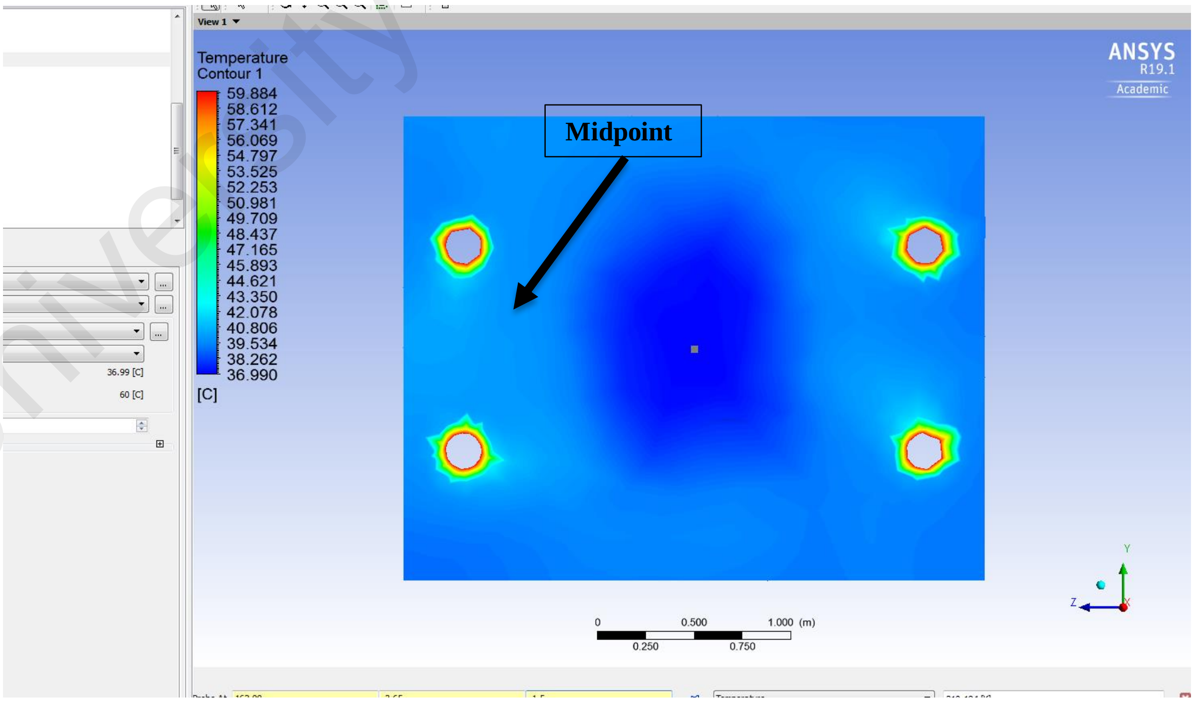


Figure 70: Model 2 - Plane D@ V_i = 1.0867m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane E;

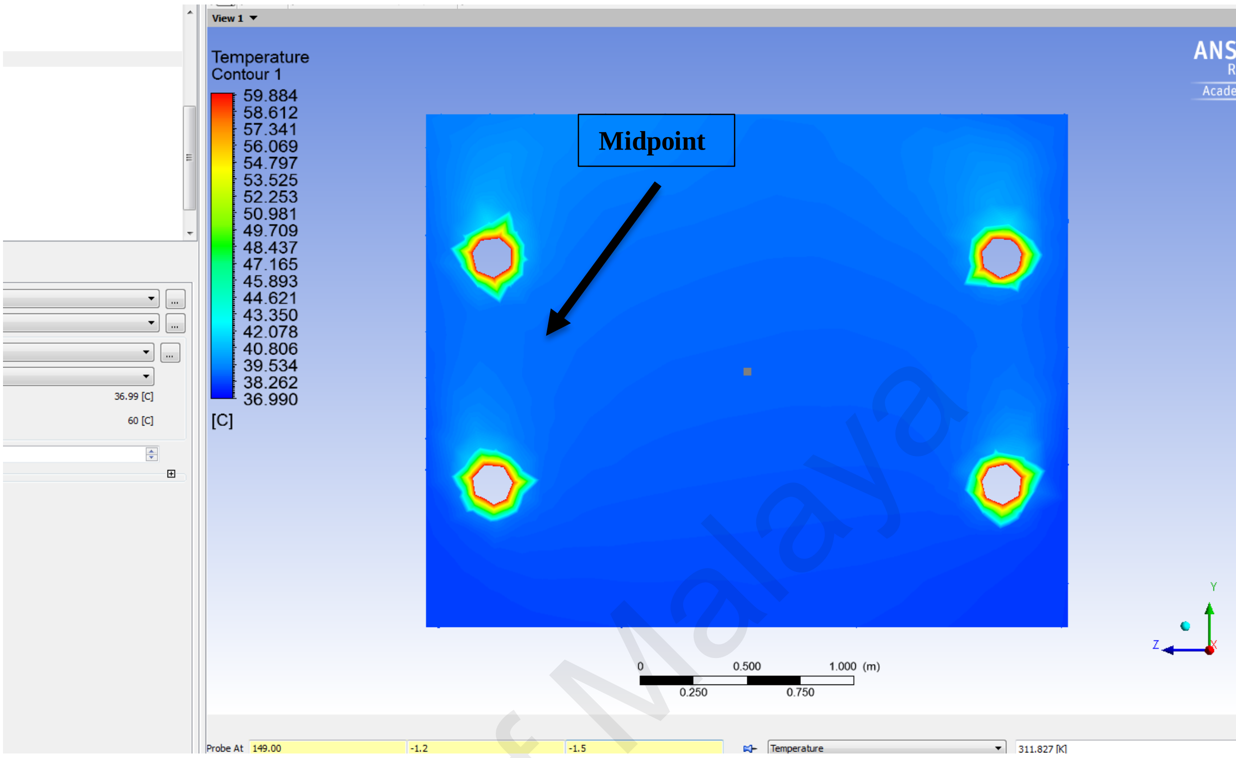


Figure 71: Model 2 - Plane E @ V_i = 1.0867m/s at 37.00°C

4.3.3 Model 2 - 20 Air Change Per Hour (ACH) with Average Ambient Temperature 33.63°C

The result did not converged at iteration no. 600.

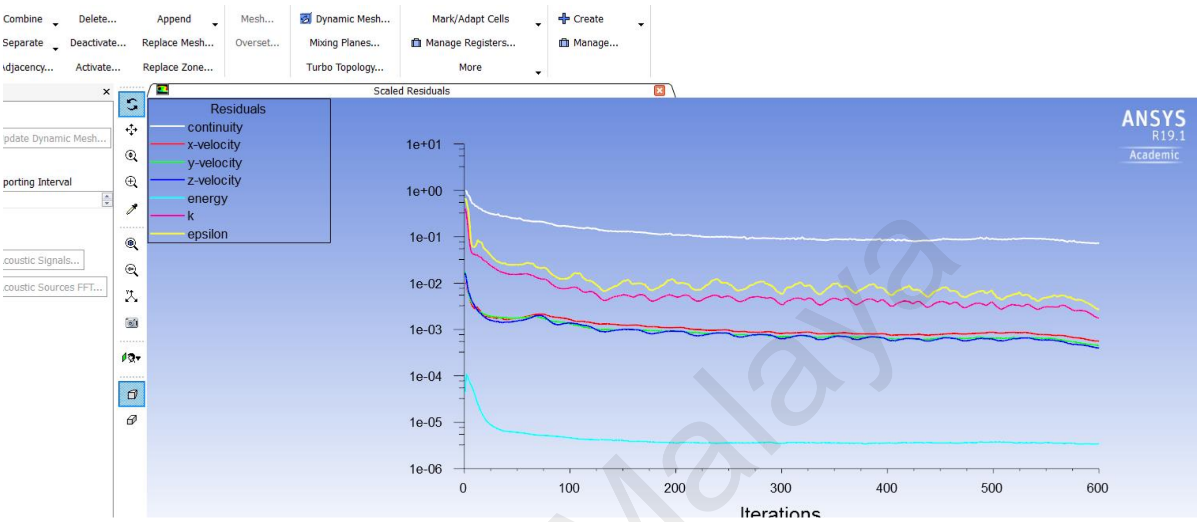


Figure 72: Model 1 - Convergence Graph @ 20ACH @ 33.63°C

Ambient Temperature (°C)	33.63 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area 1 (m^2)	1 m^2
Inlet Area 2 (m^2)	1 m^2
Inlet Area 3 (m^2)	1 m^2
Outlet Area (m^2)	1 m^2
Velocity of Intake Air (m/s)	2.1733 m/s
Total Air Flow Rate (m^3/h)	23471.64 m^3/h
ACH	20

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	33.803 °C	33.689 °C
Cutting Plane B	36.815 °C	37.775 °C
Cutting Plane C	34.464 °C	34.414 °C
Cutting Plane D	36.224 °C	33.650 °C
Cutting Plane E	35.531 °C	35.496 °C
Outlet Plane	36.478 °C	

Temperature Contour at Cross-Section of Tunnel at Plane A;

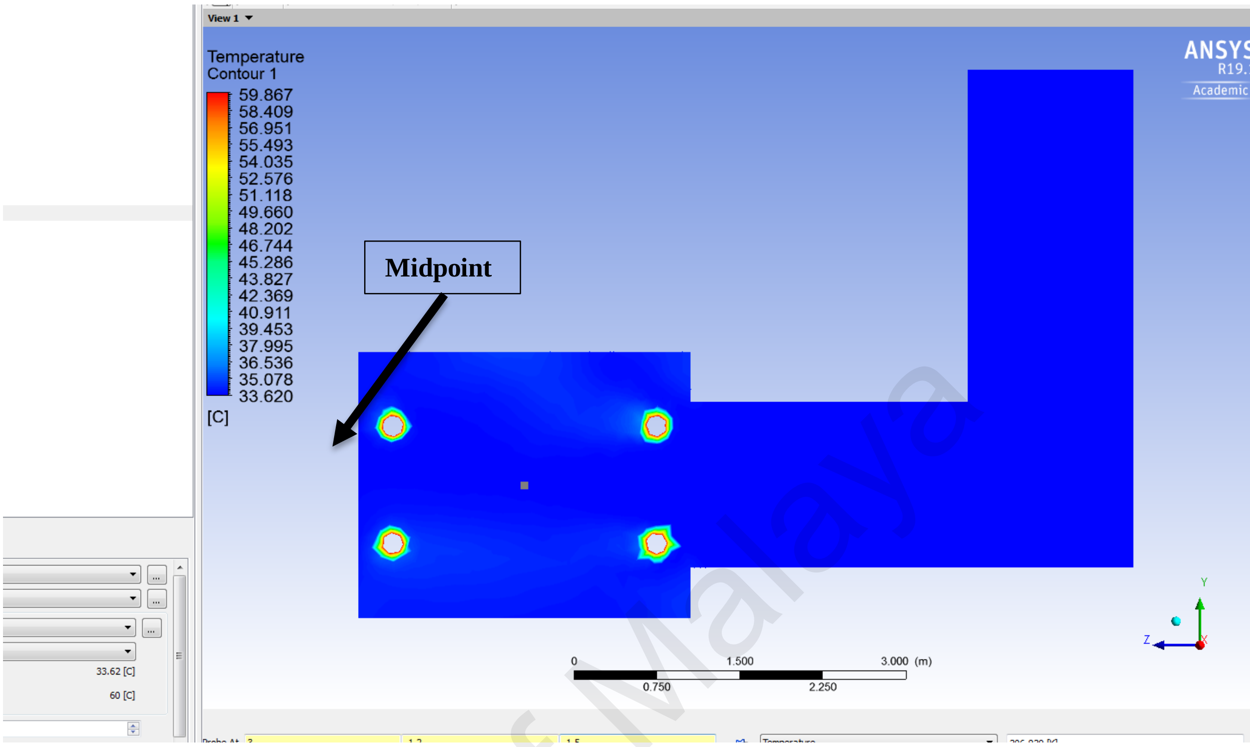


Figure 73: Model 2 - Plane A @ V_i = 2.1733m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane B;

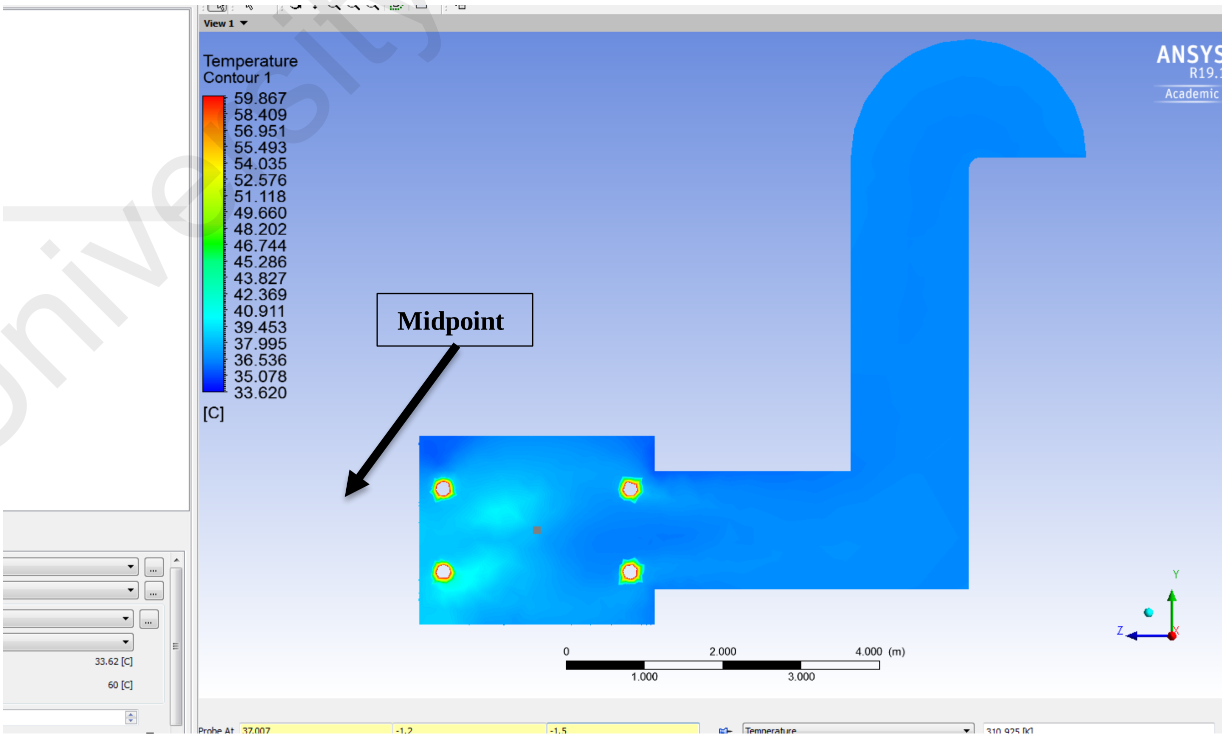


Figure 74: Model 2 - Plane B @ V_i = 2.1733m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane C;

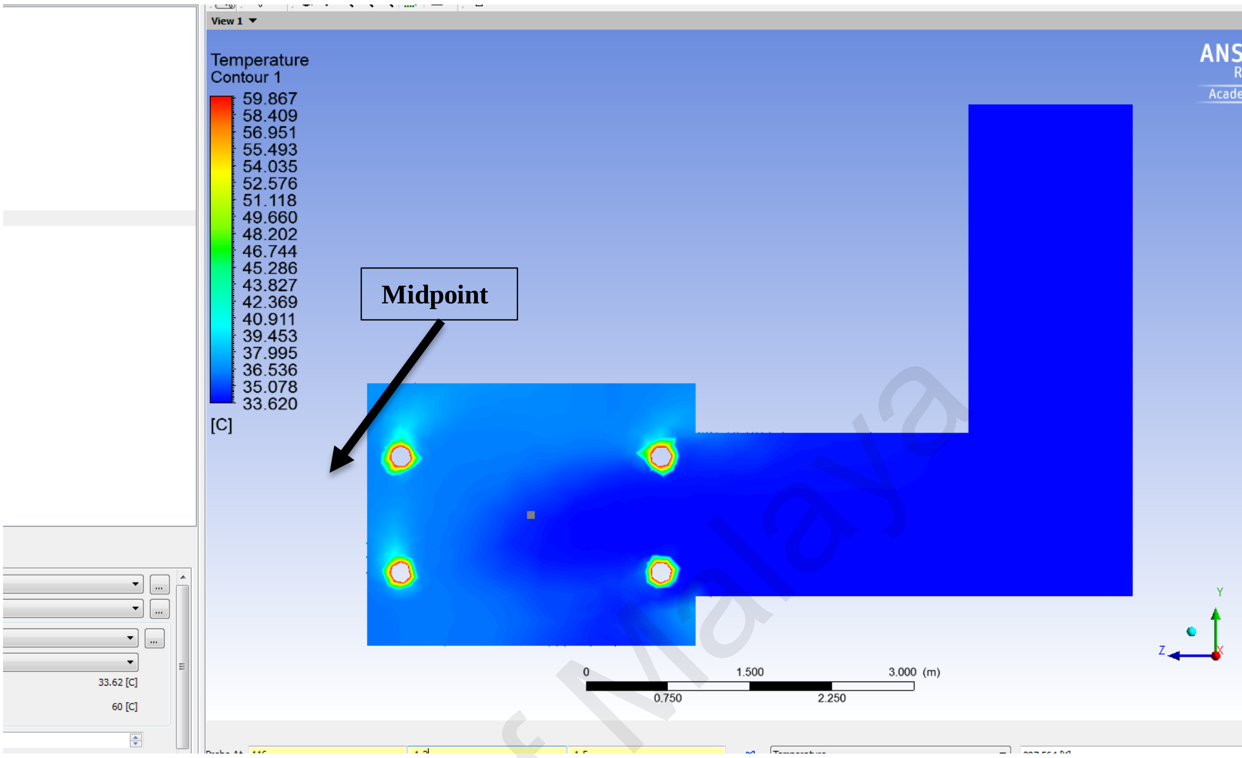


Figure 75: Model 2 - Plane C @ V_i = 2.1733m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane D;

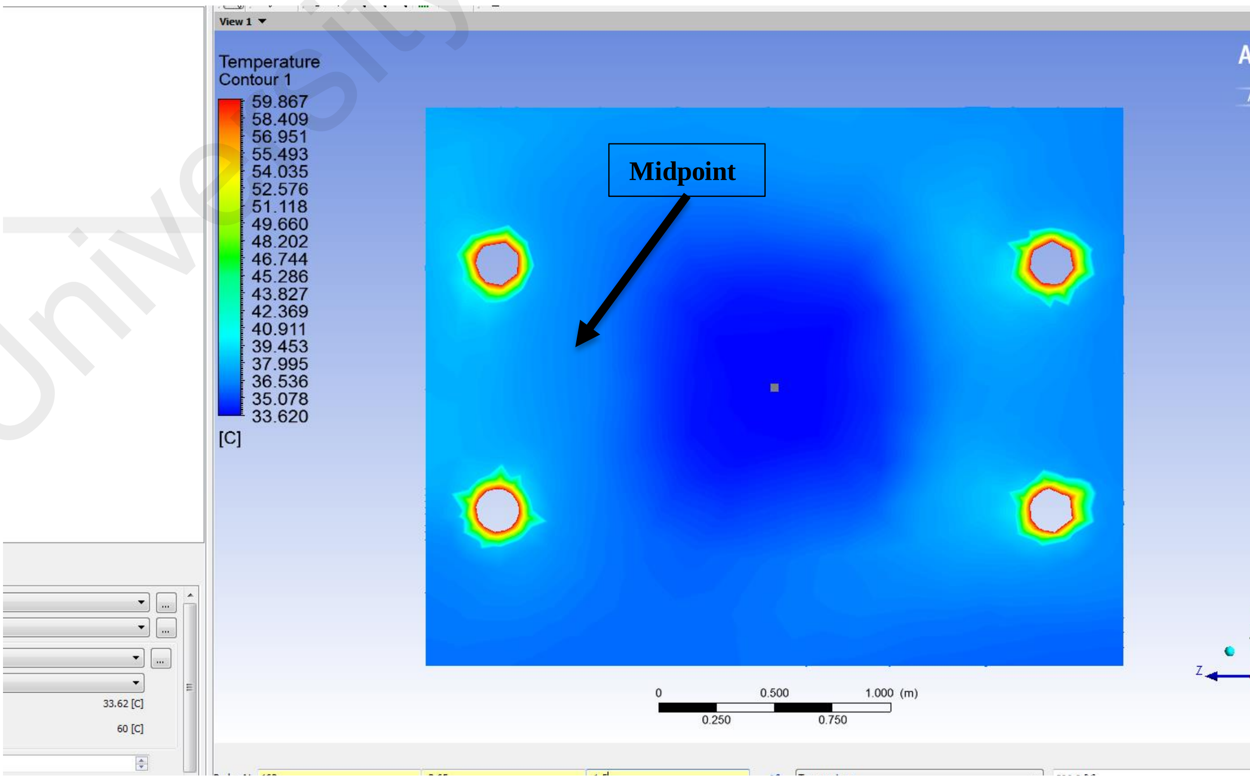


Figure 76: Model 2 - Plane D @ V_i = 2.1733m/s at 33.63°C

Temperature Contour at Cross-Section of Temperature at Plane E;

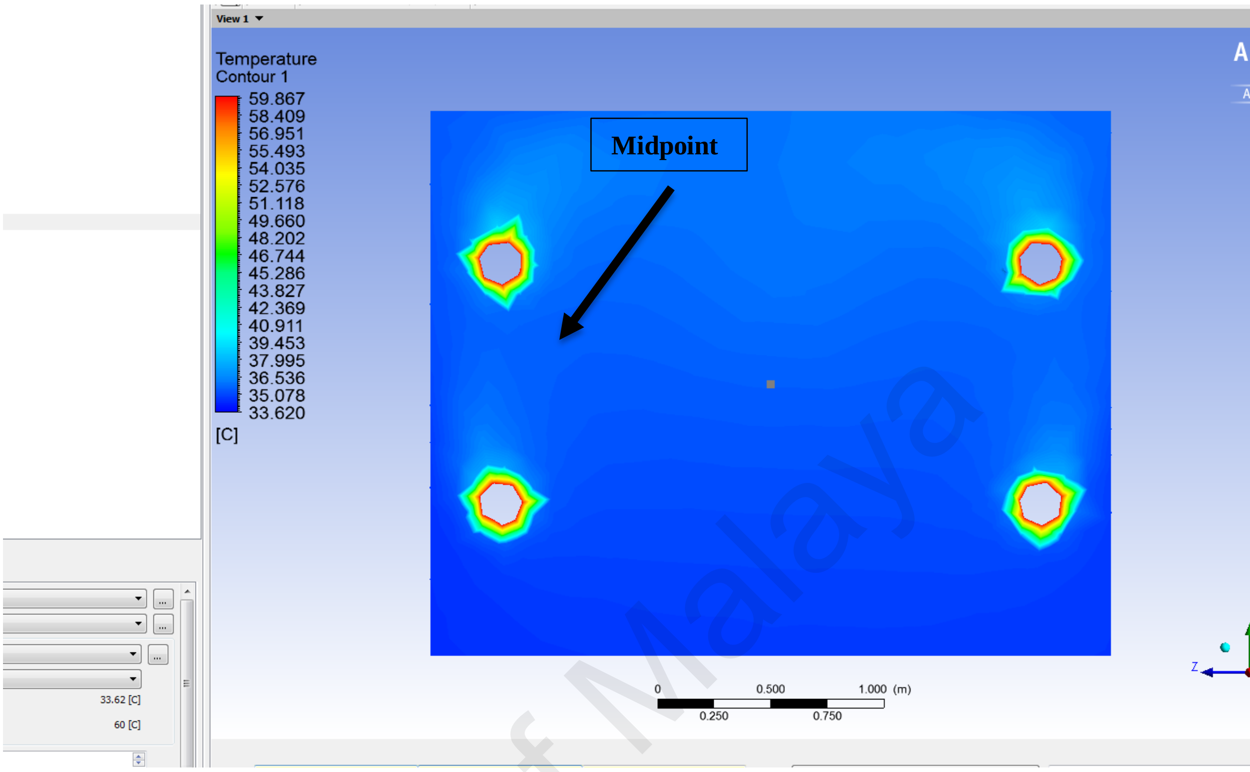


Figure 77: Model 2 - Plane E @ V_i = 2.1733m/s at 33.63°C

4.3.4 Model 2 - 20 Air Change Per Hour (ACH) with Average Ambient Temperature 37.00°C

The result did not converged at iteration no. 600.

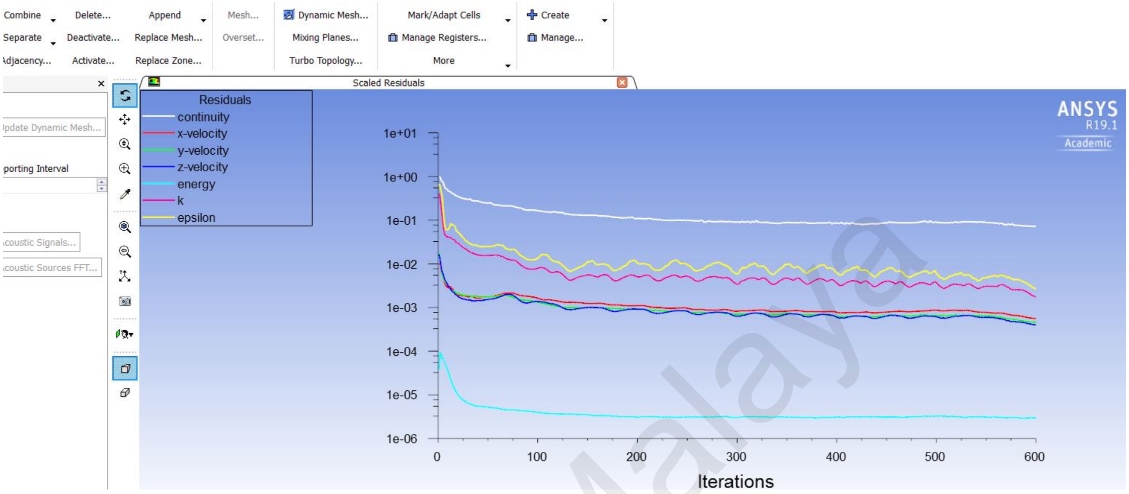


Figure 78: Model 1 - Convergence Graph @ 20ACH @ 37.00°C

Ambient Temperature (°C)	37.00 °C
Surface Temperature of Cable (°C)	60.00 °C
Inlet Area 1 (m^2)	1 m^2
Inlet Area 2 (m^2)	1 m^2
Inlet Area 3 (m^2)	1 m^2
Outlet Area (m^2)	1 m^2
Velocity of Intake Air (m/s)	2.1733 m/s
Total Air Flow Rate (m^3/h)	23471.64 m^3/h
ACH	20

	Average Temperature of Air on Plane (°C)	Temperature of Air at Midpoint (°C)
Cutting Plane A	37.151 °C	37.051 °C
Cutting Plane B	39.778 °C	40.635 °C
Cutting Plane C	37.728 °C	37.684 °C
Cutting Plane D	39.263 °C	37.017 °C
Cutting Plane E	38.658 °C	38.627 °C
Outlet Plane	39.484 °C	

Temperature Contour at Cross-Section of Tunnel at Plane A;

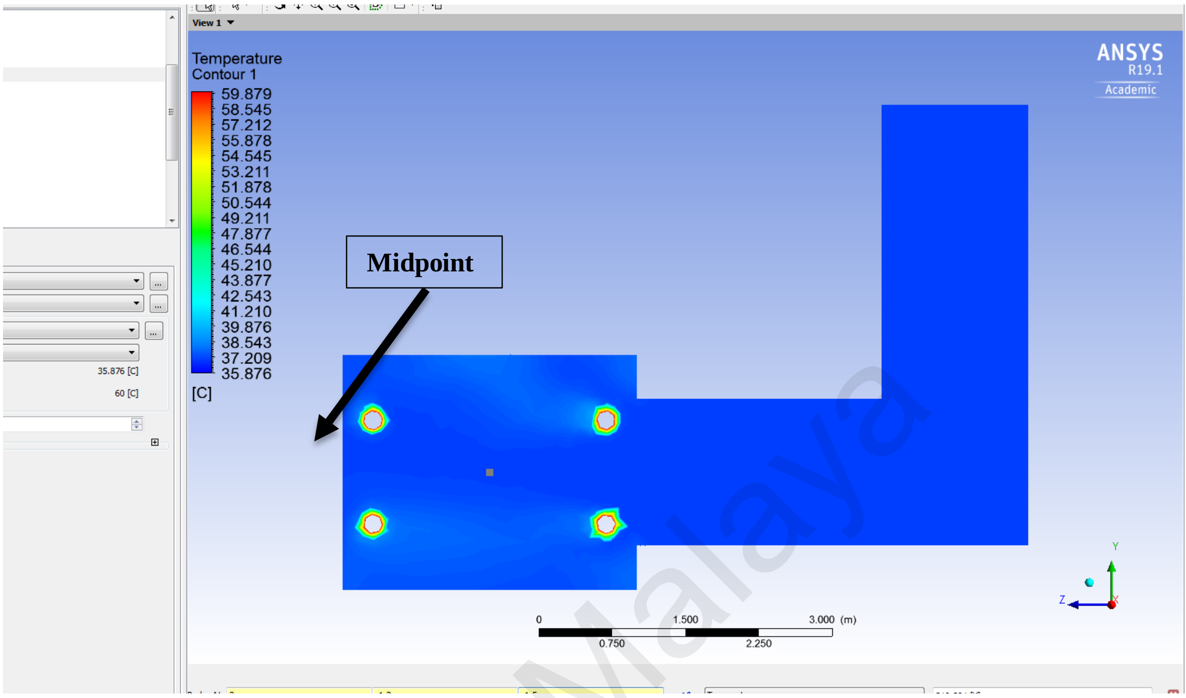


Figure 79: Model 2 - Plane A @ V_i = 2.1733m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane B;

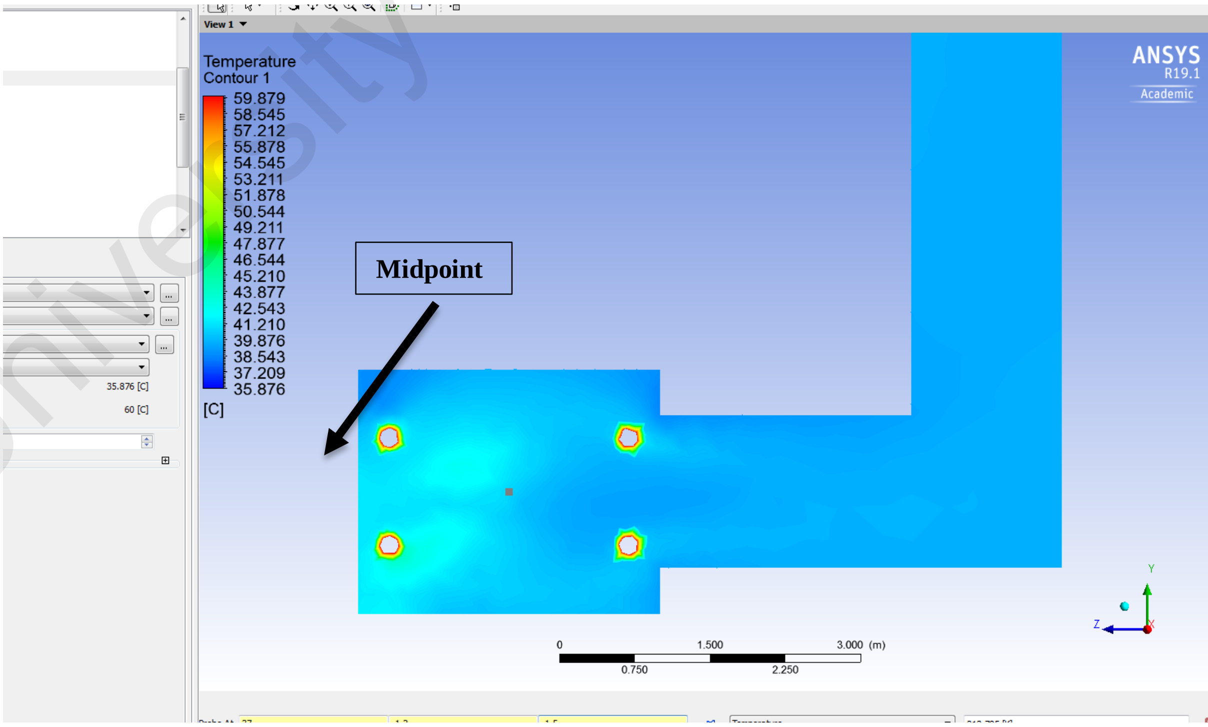


Figure 80: Model 2 - Plane B @ V_i = 2.1733m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane C;

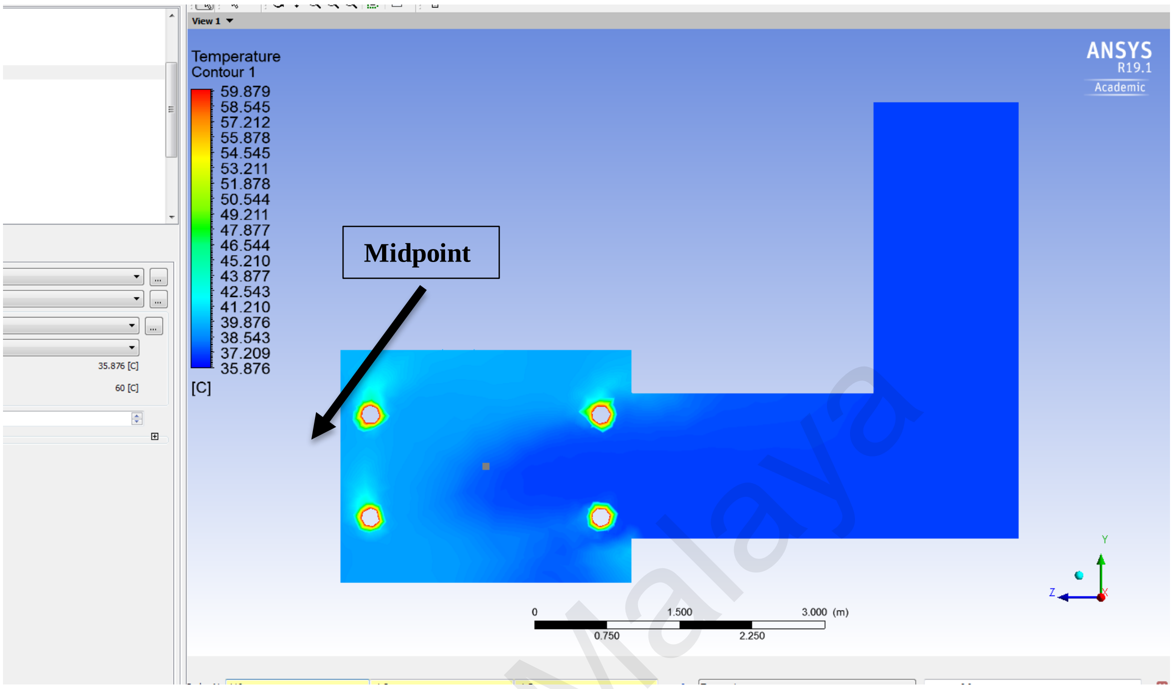


Figure 81: Model 2 - Plane C @ V_i = 2.1733m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane D;

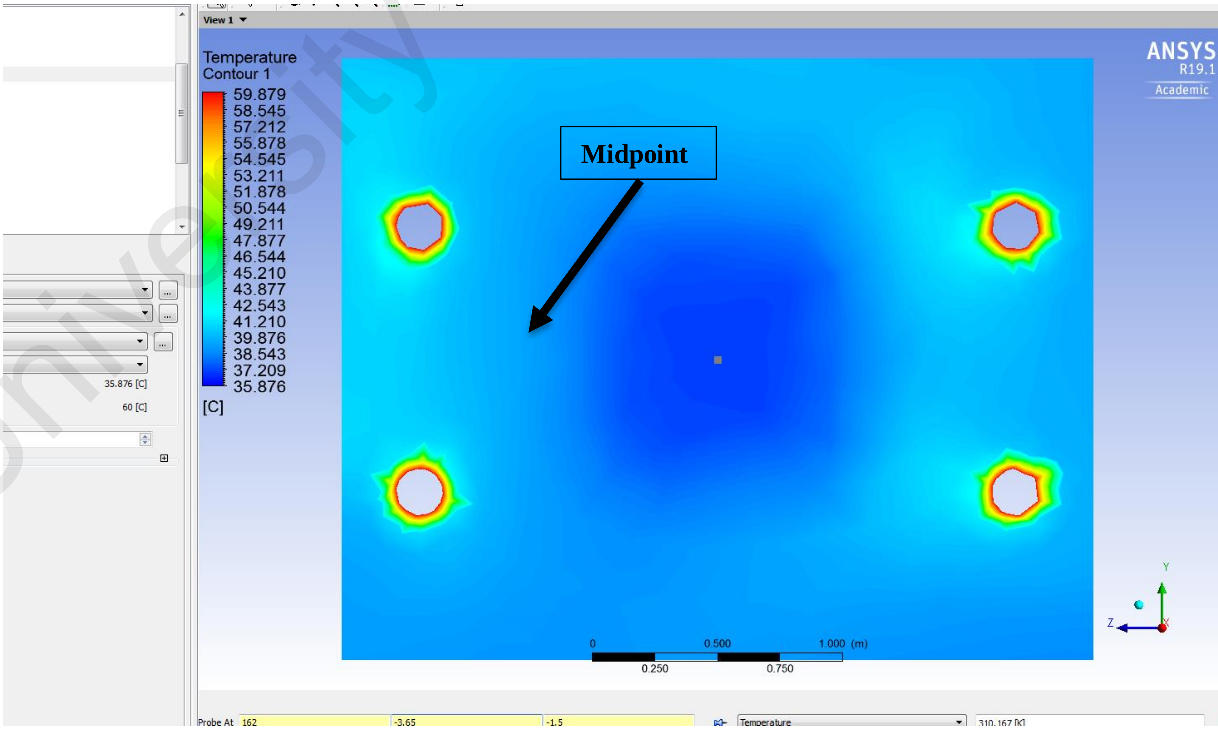


Figure 82: Model 2 - Plane D @ V_i = 2.1733m/s at 37.00°C

Temperature Contour at Cross-Section of Temperature at Plane E;

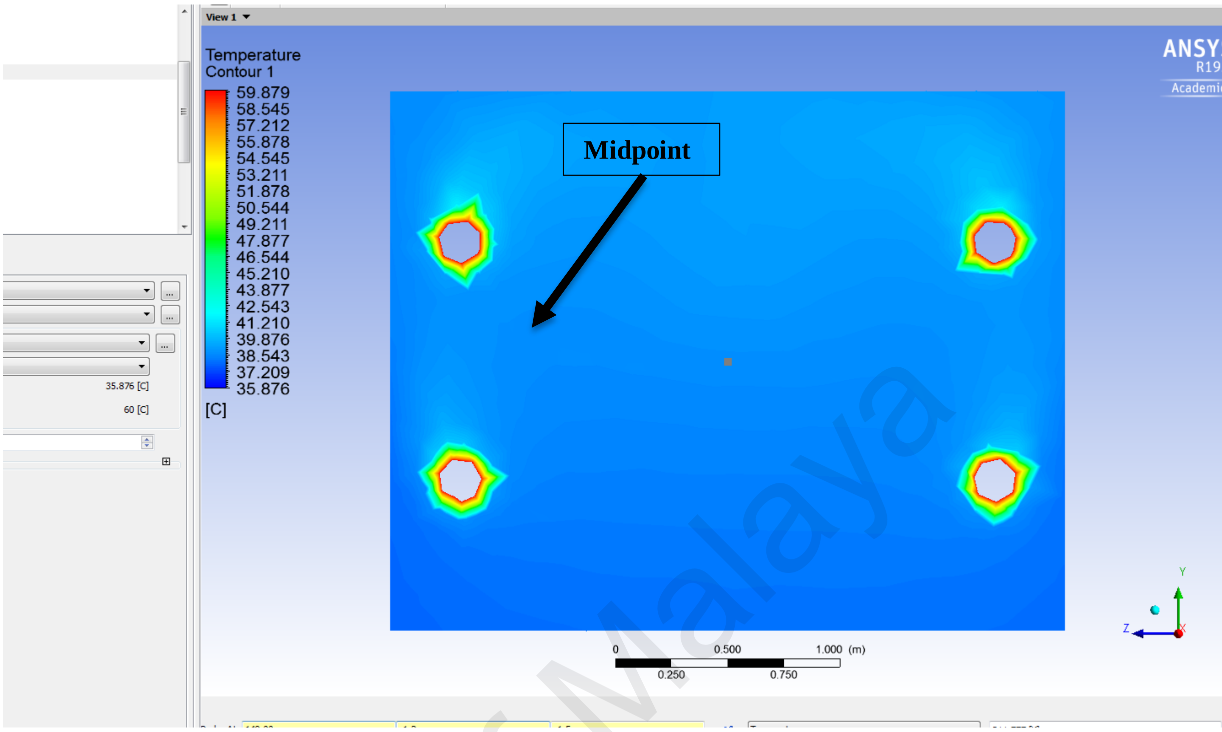
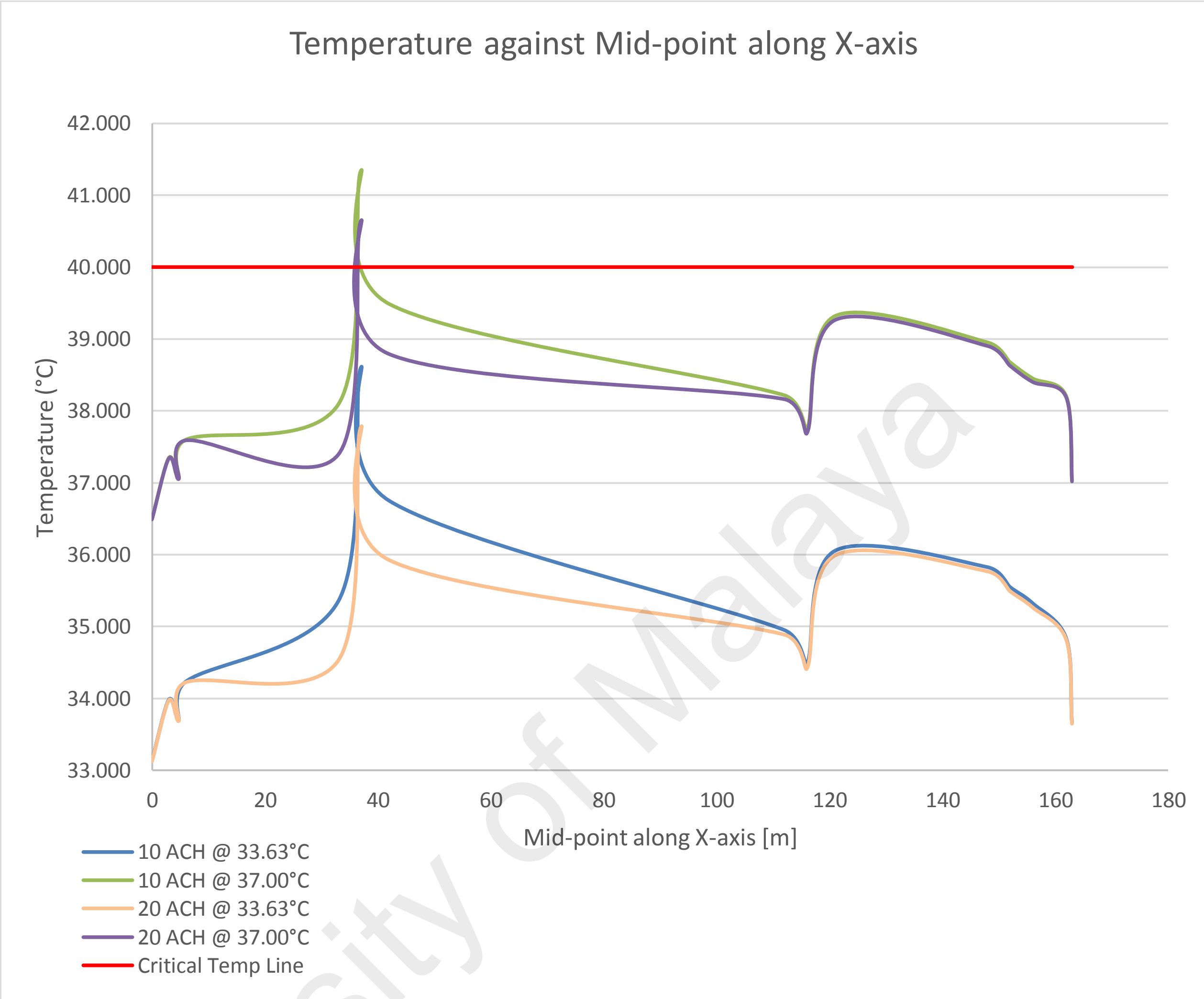
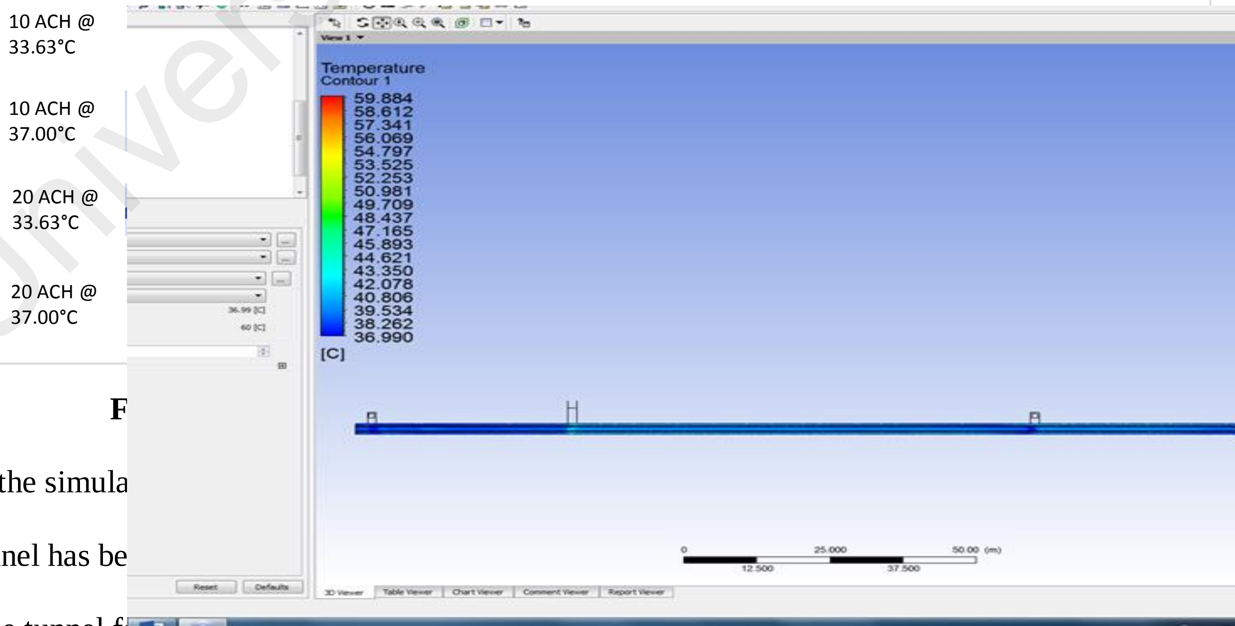


Figure 83: Model 2 - Plane E @ V_i = 2.1733m/s at 37.00°C

4.4 Discussion on Model 2 simulation results





F

All the simula

Tunnel has be

cable tunnel for 10ACH and 20ACH at average ambient temperature of 33.63°C meets the main criteria of internal temperature below 40°C. While for 10 ACH and 20ACH at above average ambient temperature 37.00°C, the middle temperature at outlet section

(X-axis: 36.25 ~ 37.75m) had overshoot 40°C and these two situation has failed to meet the main criteria.

At average ambient temperature 33.63°C, 20 ACH is the first choice to be applied for Model 2. This is because if the cable tunnel was ventilated with 20ACH, it creates more heat convections for the cables to dissipate heat and the outlet temperature also lower than by using 10ACH. The lower the internal temperature it is, the cable derating factor will be lower. Thus, high voltage cable could have higher current carrying capacity with a lower tunnel internal temperature.

While for the situation where the ambient temperature at 37°C, even at 20ACH also unable to bring down the internal temperature below 40°C. Therefore, a higher air ventilation rate (>20ACH) shall be applied to increase the convection heat transfer rate to handle such extreme situation. Besides that, additional air inlet area can also be applied to this tunnel to increase the air ventilation volume rate which possibly could resolve this issue.

However, if client do have budgetary issues to install a higher air capacity ventilation system, 10ACH with ambient air temperature 33.63°C can still be used as the middle temperature for entire tunnel still below 40°C. In fact, the client also have to bear with the risk of introducing additional ducts and fans to increase the air flow rate in case that the global temperature rise significantly in future.

CHAPTER 5: CONCLUSION & RECOMMENDATION

After individually evaluated the simulation results for both type of ventilation method, both preferred results of 20ACH under the same average ambient air temperature 33.63°C have been extracted out and plotted in the graph below for comparison.

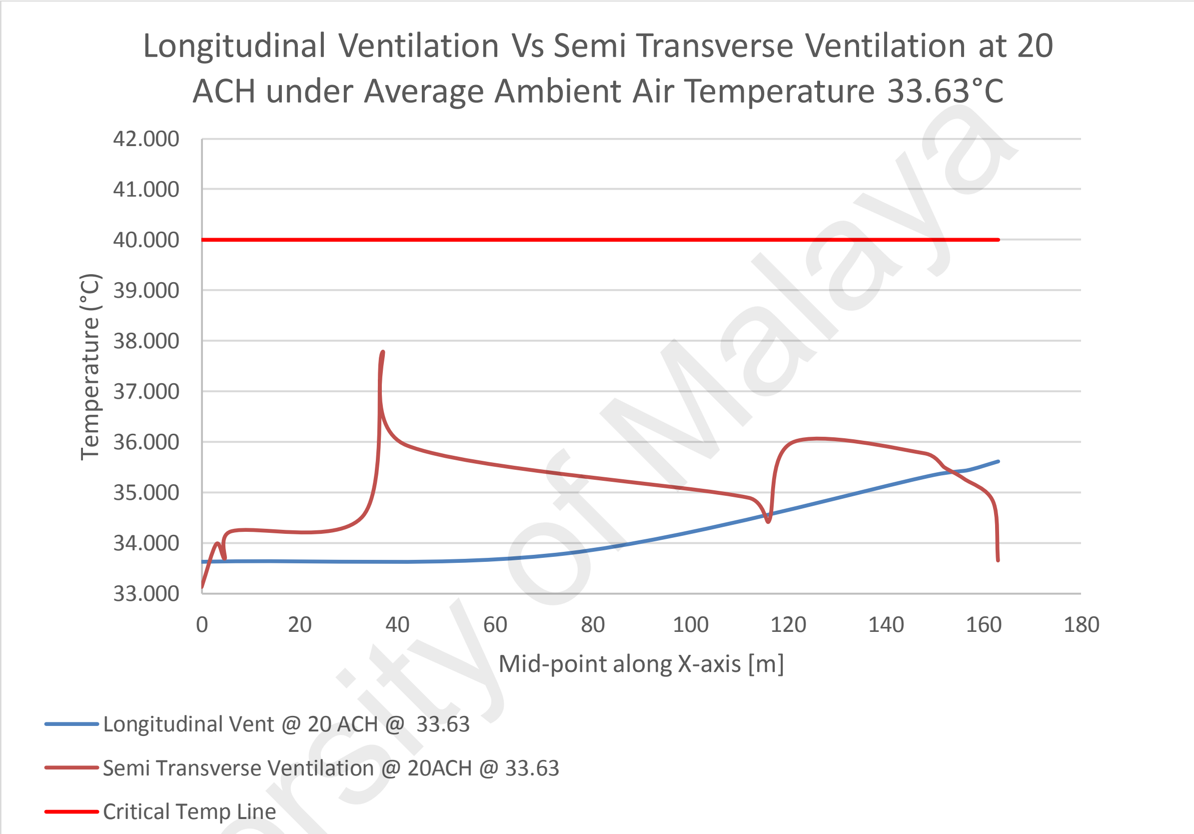


Figure 85: Longitudinal Ventilation Vs Semi Transverse Ventilation at 20 ACH under Average Ambient Air Temperature 33.63°C

It seems that longitudinal ventilation has an average lower temperature at mid-point compared to the semi transverse ventilation. Theoretically, semi transverse ventilation should perform better as it has more fresh air intake point at different points along the cable instead of longitudinal ventilation only have one. If semi transverse ventilated model has a same outlet size as longitudinal ventilated model, the average temperature of the cable tunnel may be further reducing as it may exhaust hot air efficiently. However in this case, it was a rough guess that due to space constraints on ground to build bigger ventilation shaft, which had lead semi transverse ventilation perform poor than longitudinal ventilation.

On the other hand, the temperature for longitudinal ventilation grow proportionally and as it goes further distance in X-axis. It will reach to a point where it will intersect with the critical temperature 40°C. This is the limitation of longitudinal ventilation. Whereas semi transverse ventilation could remain below the critical temp even if the cable tunnel is longer as it only required additional ventilation shafts.

Therefore, it can be conclude that Longitudinal ventilation perform better in this case study and 20ACH (0.9055m/s) with an inlet of $7.2m^2$ will cool down the cable tunnel efficiently from the range of ambient air temperature below 37.00°C. As a tropical country like Malaysia, the climate could change rapidly. Therefore, the proposed ventilation system design and air flow rate could handle tedious weather temperature as well as the heat generated by the high voltage cable. It would constantly keep the high voltage cables operate in a steady state conditions.

All the objectives have been achieved. If time allows, smoke simulation test in CFD software can be conducted to check whether the designed mechanical ventilation system able to take out the smoke within a certain time frame.

REFERENCES

Retrieved from http://www.hke.com.hk/NR/rdonlyres/2D3E993F-1BD1-4BA5-BDCD-CB1D504DA3DF/0/TunnelFactSheet24September2007.pdf

Dr. Igor Maevski (May, 2016). Recommended Aashto Guidelines For Emergency Ventilation Smoke Control In Roadway Tunnels. Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(363)_FR.pdf

Polycab HT XLPE Cable. Retrieved from http://indiancables.net/polycab-ht-xlpe-cables/

Yunus A. Cengel. Afshin J.Ghajar (2015). *Heat and Mass Transfer Fundamentals & Applications (Fifth Editions in SI Units).*

Creosteanu (June 2012). Comparison between an analytical method and two numerical methods on a given electrostatic potential determination problem. Retrieved from https://ieeexplore.ieee.org/document/6262310

M. Matsumura (June 2006).Transmission capacity design of underground power cables installed in deep tunnel. Retrieved from https://ieeexplore.ieee.org/document/1709076

ChonungKim (April 2007). Investigation on water treeing behaviors of thermally aged XLPE cable insulation. Retrieved from https://www.sciencedirect.com/science/article/pii/S0141391007000298?via%3Dihub

M. Hayashi (April 1989). Development of Water Pipe Cooling System for Power Cables in Tunnels. Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4310580

Tenaga Nasional Berhad (July 2015). XLPE Cable System Specification. Retrieved from https://www.scribd.com/document/364901467/Cable-Specification-TNB

Cable Sizing Calculation (2017). Retrieved from https://wiki.openelectrical.org/index.php?title=Cable_Sizing_Calculation

Malaysian Meteorological Department (Oct 2018). Annual Weather Data. Retrieved from http://www.met.gov.my/data/ICN20032.html

Obinna E. Igwe (2016). Cable Sizing and Its Effect on Thermal and Ampacity Cavlues in Underground Power Distribution. Retrieved from https://uknowledge.uky.edu/ece_etds/87/

Jensen,O.P (1988). Heat Transfer and Thermal Stresses in the Singapore Cable Tunnel. Retrieved from https://www.e-periodica.ch/cntmng?pid=bse-cr-001:1988:13::541

Mozen Ltd (May 2011). Design, Testing and Application of an Energy Efficient Longitudinal Ventilation System. Retrieved from https://www.researchgate.net/publication/317504514_Innovation_in_Jetfan_Design

National Grid,UK (2015). Undergrounding high voltage electricity transmission lines. Retrieved from https://www.nationalgrid.com/sites/default/files/documents/45349-Undergrounding_high_voltage_electricity_transmission_lines_The_technical_issues_INT.pdf

Yacine Mecheri (May 2013). Effect of Thermal Ageing on the properties of XLPE as an Insulating Material for HV Cables. Retrieved from https://www.researchgate.net/publication/258883586_Effect_of_thermal_Ageing_on_the_Properties_of_XLPE_as_an_Insulating_Material_for_HV_Cables

TOTL Citizen Advisory Group (April 2015). Underground vs Overhead Transmission. Retrieved from http://www.tpud.org/wp-content/uploads/2015/04/Final-Presentation-4-15-2015.pdf

Sturm P.J. (2008). Evolving Needs of Tunnel Ventilation in A Changing World. Retrieved from https://pdfs.semanticscholar.org/35e9/d123f303ab68f5ce20172ef05bb1eea3a158.pdf