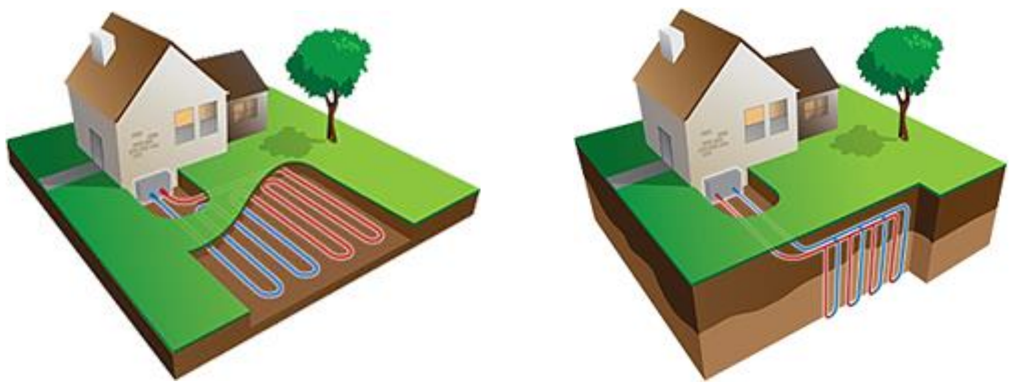
Contents

1. Introduction

1.1. Background

The increasing demand of using renewable energy has been taken as priority in today's engineering perspective all over the world. In civil engineering, energy piles, Ground Source Heat Pumps (GSHP) and geothermal energy extraction are all gaining popularity as sustainable energy systems because of their potential to reduce primary energy consumption and thus reduce emissions of greenhouse gases. They make use of renewable energy stored in the ground, providing one of the most energy-efficient ways of heating buildings. The technology is well established in North America and parts of Europe, but is at the demonstration stage in the UK. [1]

The temperature of the ground is fairly constant below the frost line. The ground is warmer in the middle of winter and cooler in the middle of summer than the outside air. The geothermal energy is bi-directional and it can be used for both heating and cooling purposes. A single efficient system can be used for both heating and cooling, eliminating the need for separate boiler/furnace and air-conditioning systems. A GSHP harnesses heat from underground by pumping water through series of buried pipes. The system can be configured as either a closed or open loop and the loop itself can be either horizontal or vertical.

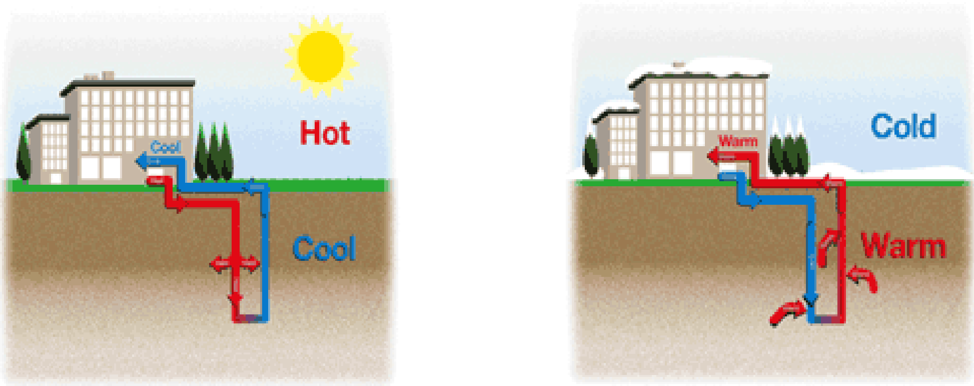


Horizontal Loop **Vertical Loop**

Figure 1.1: Two images illustrate the loop (South West Energy Services)

[1]. *Abdeen Mustafa Omer, Ground-source heat pumps systems and applications*

During winter time, even at temperatures that are considered to be cold, air, ground and groundwater contain useful heat that is continuously replenished by the sun. By applying a little more energy, a heat pump can raise the temperature of this heat energy to the level needed. Warm ground water will be pumped through cold building and transfer heat to the building providing home heating or hot water. The 'spent' colder water will then returned to the ground to form a loop. During summer time, the system is reversed to transfer heat out of the building, where it uses the cooler ground as a heat sink. The pump needs electricity to run, but the idea is that it uses less electrical energy than the heat it produces. Typically, a GSHP will deliver three or four times as much thermal energy (heat) as is used in electrical energy to drive the system.



Summer **Winter**

Figure 1.2: Two images illustrate the concept of GSHP in summer and winter (Top-alternative-energy-sources)

1.2. Objectives

This project aims to include a model building on the ground surface which will be heated up using the heat from ground water. The model building will be made using different materials to encourage or discourage heat transfer. The main outcome is anticipated to be a model experiment that includes heat transfer from the ground into model buildings. The model buildings can be changed to have materials with different U-value to encourage or discourage heat transfer between building and its environment. Heat can be extracted from ground water and used to heat up the model buildings made from different materials. Thermo-couples will be used to monitor the temperatures within the model building. The main aim of the project will be to develop different types of model buildings and establish the temperature difference that is needed to use heat from ground water efficiently to heat the buildings.

Experiments were designed to simulate the heat transfer in summer time and winter time.

- To model heat transfer from ground water to the building and back to the ground water
- To develop different types of model buildings (different U values)
- To establish temperature difference in order to heat the building efficiently

1.3. Structure of the report

The report starts with theory and design of the experiment in section 2. It explains how series of experiments are designed based on existing theories. It illustrated purpose of different experiments and why such experiments are designed. Assumptions behind the theoretical development are explained.

Section 3 exhibits the experiment apparatus, describes the running of the experiments and how data is obtained. The sources of error are explained in this section.

Section 4 is the most important section in this report. It combined results and discussion. Calculations are performed in this section as well.

Section 5 contains the main findings and possibly ideas for future work.

2. Theory and Design of Experiment

2.1. Experiment Design

This project aims to build on the *3D8 Flow of ground water and heat experiment* that looked at heat transfer into ground. The purpose of 3D8 experiment is to identify the similarities between the flow of ground water and the flow of heat in soils. The experimental data is used to estimate the hydraulic conductivity K of the soil and the thermal conductivity λ of the soil. The existing apparatus for this experiment is a tank of sand with water table above ground level. There is an extraction well inside the tank connecting to a cartridge heater and centrifugal pump. The pumping flow rate into the well and the heat output from the cartridge heater can both be adjusted. This project will extend this to include a model building on the ground surface which allows ground water to flow through it.

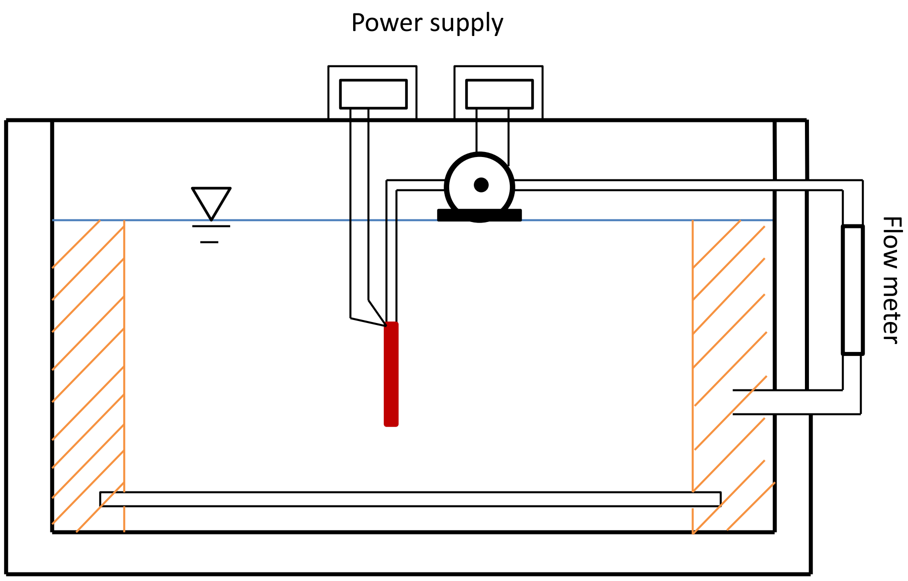


Figure 2.1 Schematic diagram of the cross-section of the 3D8 model

The objective of this section is to produce a model building, which can allow ground water flow through it under different conditions. First of all, the size of the model building should be decided and fixed through all experiments. It is shown in *Figure 2.2* that depending on latitude, the temperature beneath the upper 10 meters of ground surface maintains a nearly constant temperature between 8 and 12 ℃. The cartridge heater is installed inside the tank at a depth of 200 mm with soil depth of 300mm. In order to match the real case, a 1:50 model would be adequate.

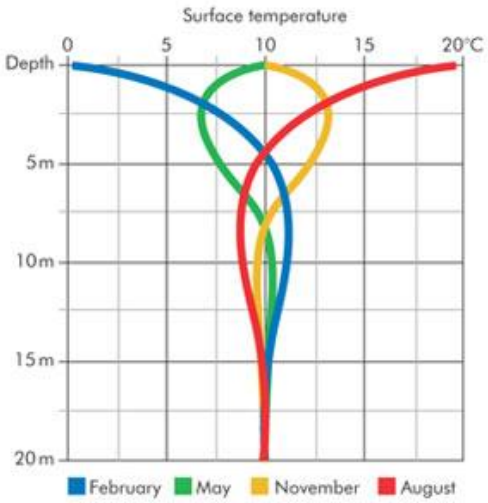


Figure 2.2: Temperature of ground throughout the year (Dimplex)

The size of the model building will be 50 x 50 x 20 mm as shown in *Figure 2.3*. Thermocouples will be installed at the inlet of flow, outlet of flow and on the block to monitor temperatures. The flow pipe is chosen to be 1/4'' BSP which has diameter of 13.2 mm.

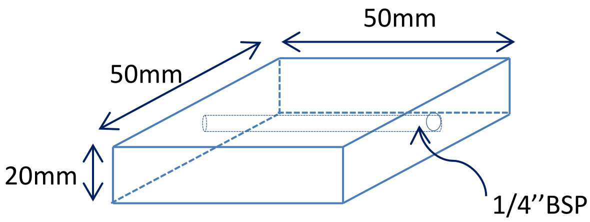


Figure 2.3: The drawing diagram of model building

The model building was designed using two different materials: Aluminum alloy (Dural) and Perspex (Plastic). Metal and plastic have great difference in specific heat capacity which means the amount of heat required to change the same temperature of an object is great. For aluminum alloy, the specific heat capacity is 380J/kgK whilst the specific heat capacity for Perspex is 1300J/kgK. Perspex will require much more heat to raise the same temperature than aluminum alloy. Therefore, the U-values which signify the thermal conductivity per unit area of the material can be calculated.

We can investigate how model buildings with different U-values encourage or discourage heat transfer between buildings and its environment.

Moreover, whether the building is partly sunken in ground water or completely open to air has an effect on heat transfer as well.

To sum up, three sets of experiments are therefore designed.

1. A: Al alloy block partly sunken in groundwater
2. B: Al alloy block completely contact with air
3. C: Perspex block completely contact with air

During summer time, the groundwater is cooler than ambient air. When cooler ground water is flowing through warmer building, the heat of the building will be transferred to the groundwater. As a result, the temperature of the water flowing in will rise and the temperature of the building will drop. During winter time, the ground water is hotter and the temperature of water flow in will decrease while the temperature of the building will increase. In order to model the real cases, series of experiments are designed.

1. Base line test run for 24 hours with the pump working at lowest pumping rate, i.e. 0.3 litre/min
2. Base line test run for 24 hours with heater working at 20 volts
3. Pumping at 0.3 litre/min and heater working at 30 volts for 2 hours
4. The model building is cooled by ice and Pumping at 0.3 litre/min and heater working at 30 volts

For each set experiment (A, B and C), there will be four sub experiments (1-4) running. *Table 2.1* below will show the abbreviation used for each experiment.

Table 2.1 Experiment Design

	24h 0.3l/min	**24h 20V**	**2h 0.3l/min+ 30V**	**Ice test 0.3l/min+ 30V**
Al alloy (in water)	A1	A2	A3	A4
Al alloy (in air)	B1	B2	B3	B4
Perspex (in air)	C1	C2	C3	C4

2.2. Experiment Theory

Four temperatures are measured in each experiment:

T1: temperature 20mm away from the heater in the soil deposit
T2: inlet temperature of the block
T3: temperature of the block
T4: outlet temperature of the block

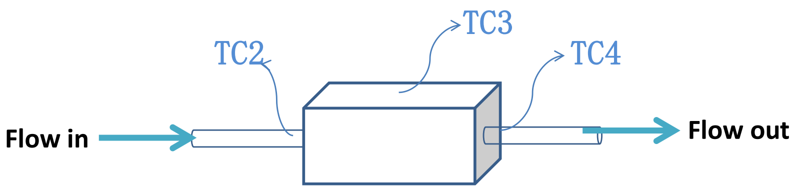


Figure 2.4 Temperature logging illustration

The theory involved in this project is simple. The heat transfer balance is the key.

Heat transfer from water to block = Heat gain by the block + Heat loss to ambient air

More detailed calculation is shown in Section 4 and Section 5

3. Apparatus and Experimental Techniques

3.1. Apparatus

The schematic experiment set up is shown clearly in *Figure 3.1*. The water is pumped out from the ground at chosen rate, pass through the building block and back to the ground through flow meter. The cartridge heater is located in extraction well and the heat output could be altered by setting different voltages. There are four thermocouples connected to the data logger measuring the temperature at four different points as mentioned in section 2.2.

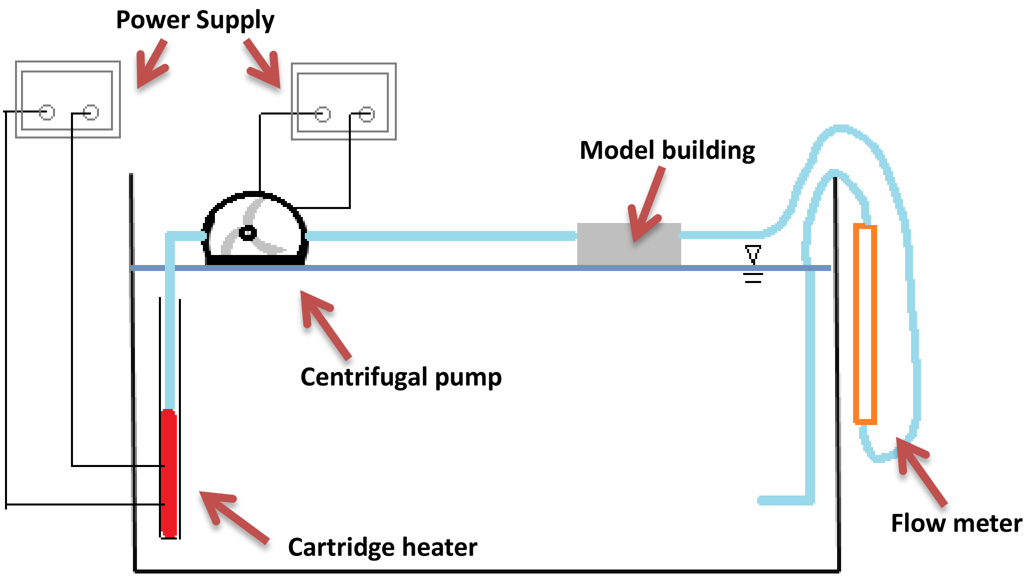


Figure 3.1 Schematic Experiment Apparatus

Figure 3.2 Experiment Apparatus

The temperatures are recorded via thermocouples and the detailed connection of thermocouples to the model building is shown in *Figure 3.3*. The plastic tube is connected to the block via a metal tube connector. The thermocouples are glued on the inlet and outlet metal connector which will provide the inlet/outlet temperature reading. Other thermocouples are glued onto the model building itself to measure the temperature of the block. The temperatures are then logged into computers via PicoLog data logger.

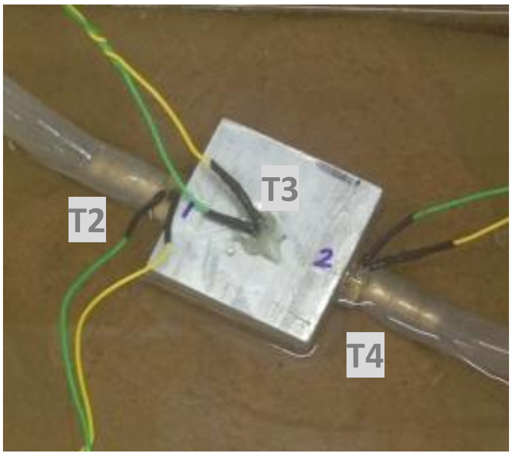


Figure 3.3 Detailed connections of thermocouples to the model building

For experiment set B and C, the block is separated from the ground water by four little supporting wood blocks under each corner of the model building. The size of four wood blocks is made to be as small as possible which enables the largest possible area of the model building open to the ambient air.

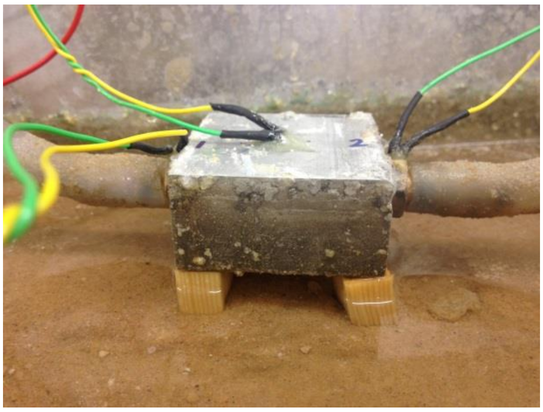


Figure 3.4 Wooden blocks supporting model building

3.2. Properties of model building

Table 3.1 Properties of model building

Material	Mass	Specific heat capacity	Thermal Conductivity
Al alloy	0.150kg	380 J/kgK	160 W/mK
Perspex	0.0687kg	1300K/kgK	0.25 W/mK

3.3. Sources of error

1. Temperature

First of all, the temperatures at inlet and outlet are measured on the metal tube connector instead of directly measuring the ground water flow. Although metal is good conductor, there are still errors in temperatures. The temperature change of the block and ground water flow is small. Therefore, even small errors could yield different results from the experiment.

Secondly, the ambient air temperature, i.e. the room temperature is not constant through each set of experiments, as the length of each experiment is long. The room temperature is varying due to the heating in the room, number of people in the room, times of entering room etc. Especially for 24 hour tests, the heating is off during the night and the temperature in the room dropped significantly.

Moreover, in order to model winter condition, ice cubes were added to the building as shown in *Figure 3.5*. However the ice cubes are added to the model building by hand. When ice cubes are in contact with the metal connector or the thermocouples, errors are brought to the results.

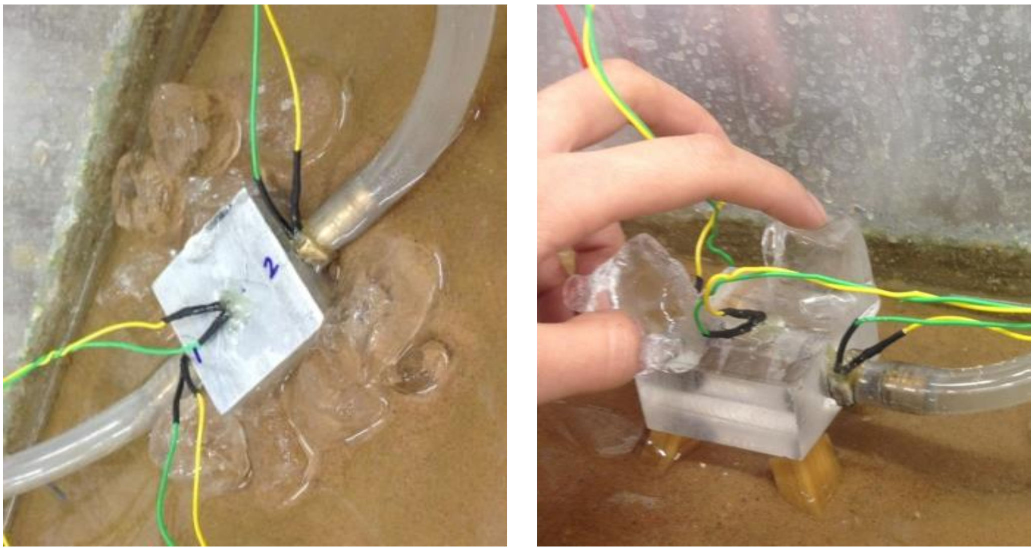


Figure 3.5 Ice cube tests A4 and C4

2. Flow rate

Although the flow meter is calibrated before, it is often found that air bubbles entered the pump and reduced the flow path. This brought errors in the measured flow rate. Occasionally, it was found that the flow rate is not at desired level even it is set correctly at the beginning of 24h test. More discussion in the flow rate errors will be presented in later sections.

4. Results and Discussion

4.1. Set A experiments: Al alloy model building partly sunken

4.1.1 A1: 24h baseline experiment with pump rate at 30 liter/min

In this experiment, the heater is not turned on and groundwater was pumped through the model building. As shown in *Figure 4.1* below, the inlet flow temperature (T2) and the outlet flow temperature (T4) are the same throughout the experiment. This means there is no heat transferred from water to the block or from block to water. The model building is partly sunken in ground water. The temperature of the block is influenced by the water under the block and the ambient air. The effect of flowing ground water is very small. The block temperature (T3) is higher than the water flow temperatures (T2 &T4). The reason for this phenomenon is the high room temperature. In reality, the ambient temperature will be much lower. Although the test result did not model the reality successfully, the apparatus was tested and found to be very sensitive and accurate.

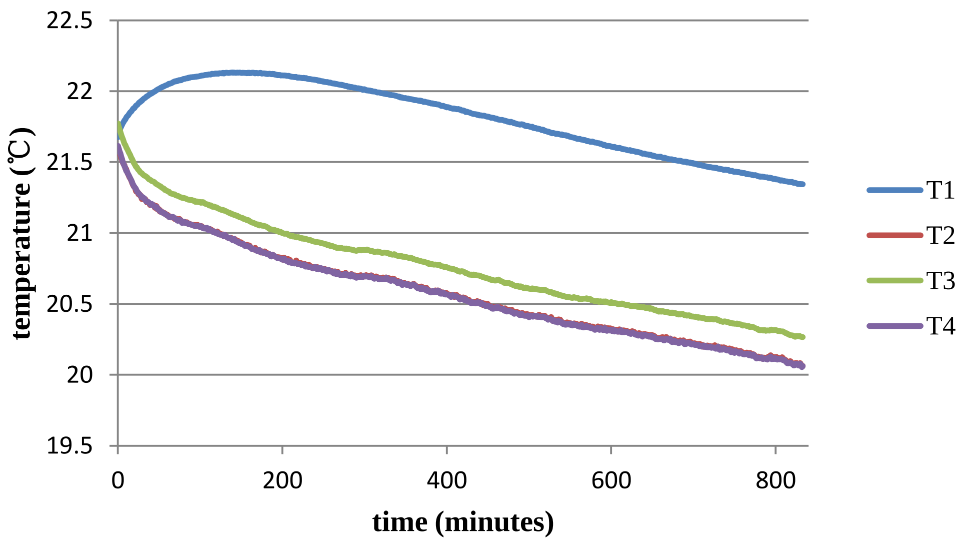


Figure 4.1 Temperature against time graph for A1

4.1.2 A2: 24h baseline experiment with heater at 20V

In this experiment, only the heater inside the tank is turned on at 20V, the pump is not working. This means there is no ground water flowing through the model building. Therefore, the inlet (T2) and outlet (T4) temperatures are the same. The only factors change the temperature of model building is the ambient temperature and the temperature of ground water. This experiment is done during the week when the heater in the room has been switched on and off at different time and there were people moving in and out of the room. This is the reason why fluctuations are observed in *Figure 4.2*.

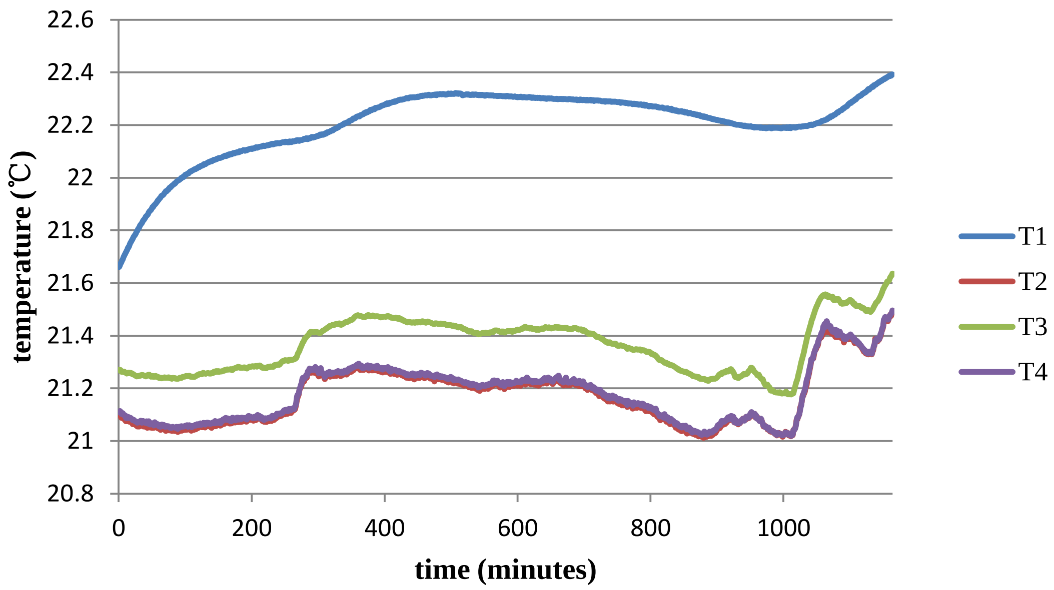


Figure 4.2 Temperature against time graph for A2

4.1.3 A3: 2h test with pump rate at 30 liter/min and heater at 30V

In this experiment, the pump and the heater are working together. The outlet temperature (T4) is higher than the inlet temperature (T2). Cooler ground water comes in to model building and warmer ground water leaves the building. This means heat has been transferred from the building to the ground water. This is modeling summer condition as building got cooled down by flowing ground water. As the modeling building is partly sunken in water, the temperature of the building will be largely affected by the temperature of ground water beneath it. Therefore, the trend of block temperature (T3) is the same as the trend of ground water temperature (T1) and T3 stays quite high.

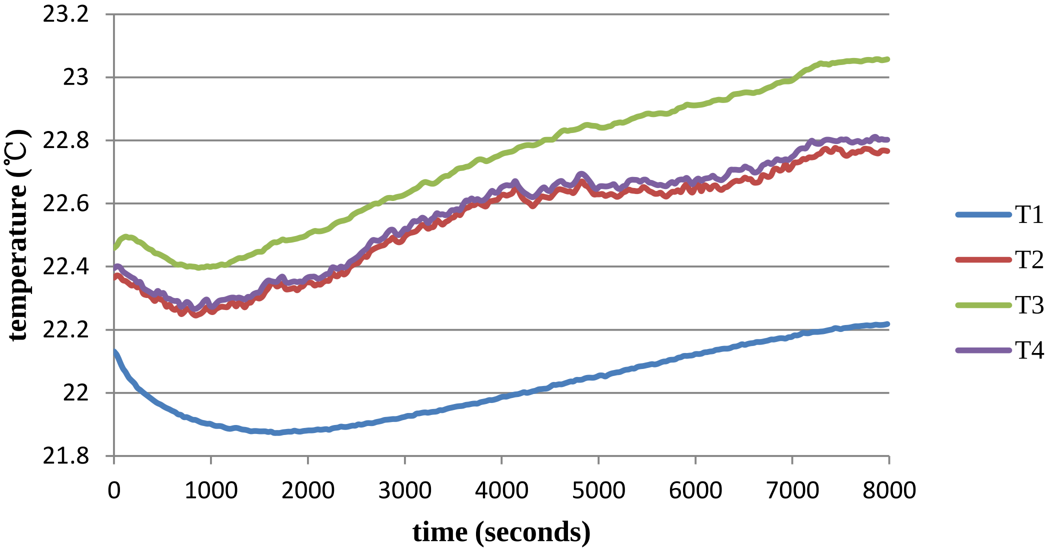


Figure 4.3 Temperature against time graph for A3

4.1.4 A4: Ice cube test with pump rate at 30 liter/min and heater at 30V

In this experiment, ice cubes were added to the model building once the previous ice cubes have melted. This is the reason why there are four significant fluctuations in *Figure 4.4* which shows the overall results. The second fluctuation is the best result among the four and it will be analyzed.

From the second fluctuation, it is shown that the block temperature (T3) is the lowest due to the contribution of ice cubes. Inlet temperature (T2) is higher than outlet temperature (T4) and heat has been transferred from ground water to the colder building. This experiment successfully modeled the winter condition.

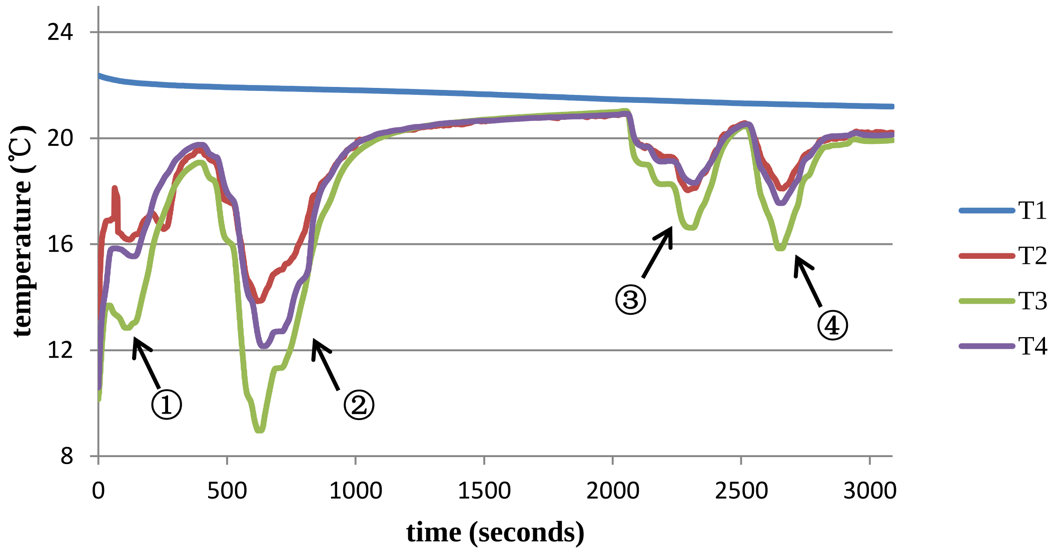


Figure 4.4 Temperature against time graph for A4

4.2. Set B experiments: Al alloy model building above ground water

4.2.1 B1: 24h baseline experiment with pump rate at 30 liter/min

In this experiment, the model building is supported by four small wood blocks under four corners as shown in *Figure 3.4.* As a result, the block temperature will only be affected by the flowing ground water into the building and the ambient temperature. The outlet temperature (T4) is higher than the inlet temperature (T2) until reaching the limit at 1100min. When ground water is flowing through model building, heat has been transferred from the building to water. The inlet temperature and outlet temperature are being confusing after 1100min. The reason for this is that the heating in the room has been switched on which destroy the steady state.

The result can be compared to experiment A1 shown in *Figure 4.1*. Experiment B shows a better result than experiment A as there is temperature difference between the inlet and the outlet. When the model building is not embedded in water, the effect of heat transfer is clearer.

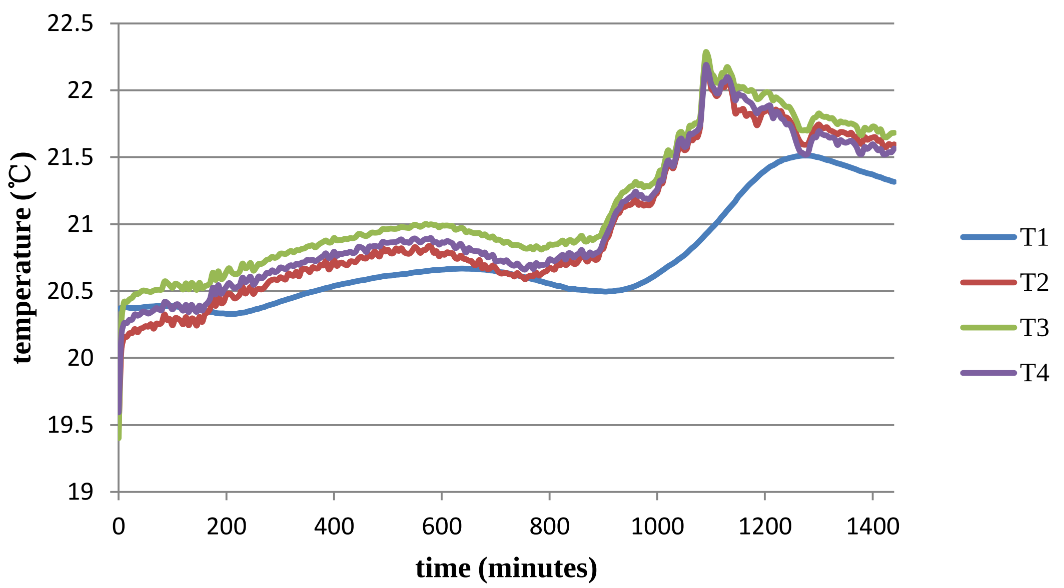


Figure 4.5 Temperature against time graph for B1

4.2.2 B2: 24h baseline experiment with heater at 20V

In this experiment, the outlet temperature (T4) is higher that the inlet temperature (T2) throughout which indicates that the heat has been transferred from building to the water. However, the water inside the building is not flowing. It is the room temperature that is affecting the block temperature (T3) and indirectly affected the water temperature (T2 and T4) inside the building. The room has a higher temperature than the temperature of the block. Therefore, heat is transferred from the building to the water inside the building.

Comparing to experiment A2 shown in *Figure 4.2* where the block temperature (T3) is much higher than T2 and T4. When separate the block from the groundwater, the temperature of block is not affected by the temperature of heated ground water.

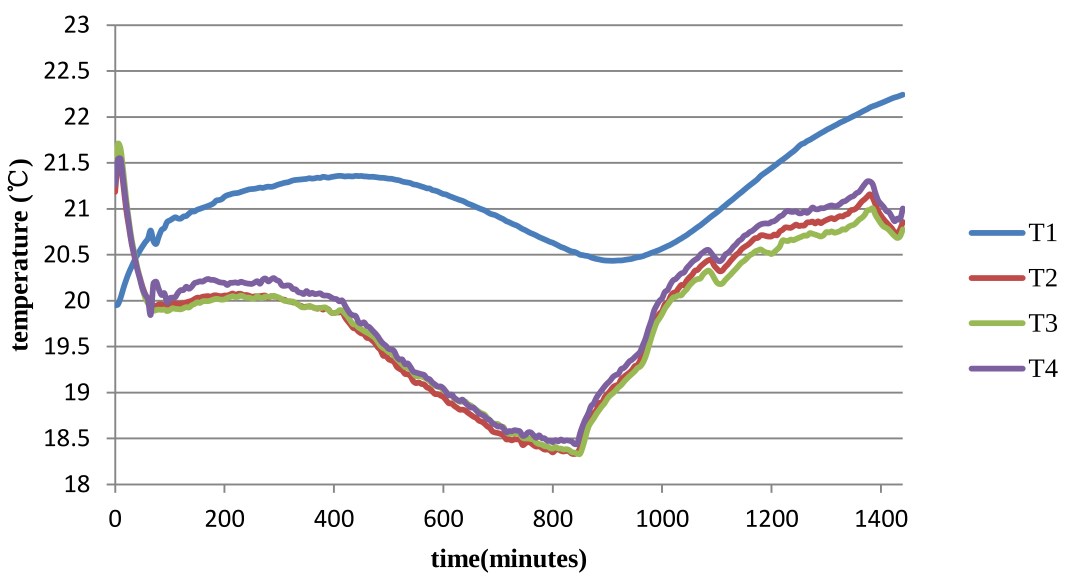


Figure 4.6 Temperature against time graph for B2

4.2.3 B3: 2h test with pump rate at 30 liter/min and heater at 30V

In this case, the heater is on at 30V and pump is working at 0.3l/min. From *Figure 4.7* above, in general, the outlet temperature (T4) is higher than the inlet temperature (T2) and the block temperature is somewhere in between. This is modeling summer time where heat has been taken away from building by the flowing groundwater. Cooler ground water flows in and warmer ground water flows out.

Comparing to experiment A3 shown in *Figure 4.3*, B3 has a much lower block temperature, thanks to the four supports.

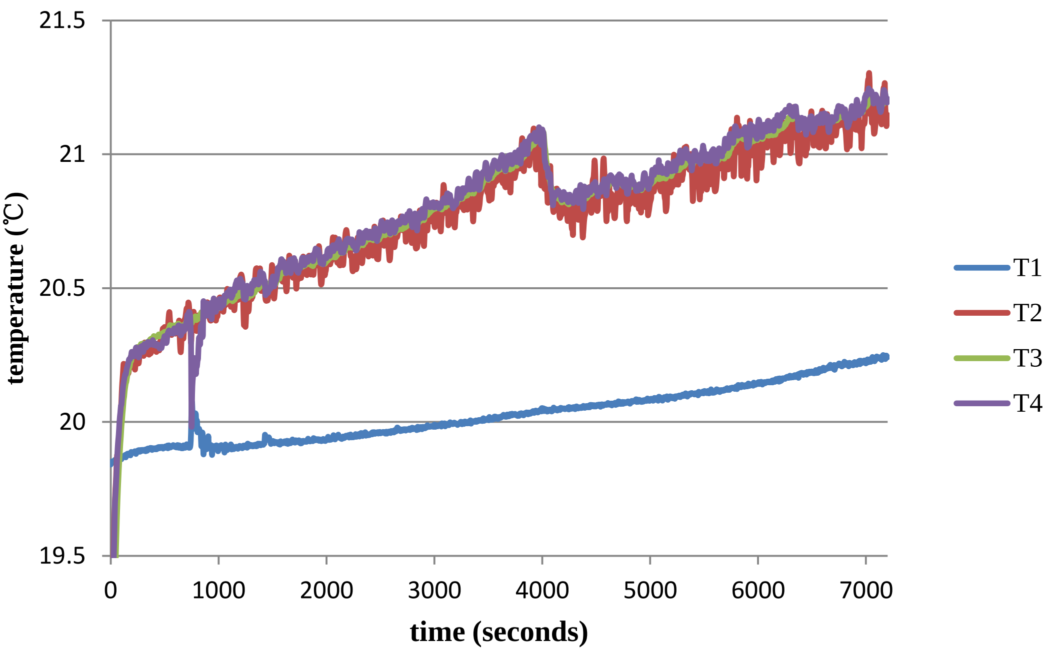


Figure 4.7 Temperature against time graph for B3

4.2.4 B4: Ice cube test with pump rate at 30l/min and heater at 30V

Again, this is an ice cube test in which ice cubes were added to the model building once the previous ice cubes have melted. This is the reason why there are four significant fluctuations in *Figure 4.8* which shows the overall results. The second fluctuation is considered to be the best result. This experiment is modeling the winter condition where the model building is very cold. It is clearly shown in graph above that the inlet temperature (T2) is higher than the outlet temperature (T4). This means the warmer ground water flows into the building and heat has been transferred from water to the building and hence cooler ground water flows out from the building.

The results shown in experiment A4 (*Figure 4.4*) is very similar to this experiment. The effect of supporting the model building is not obvious since the temperature of building (T3) is governed by ice cubes.

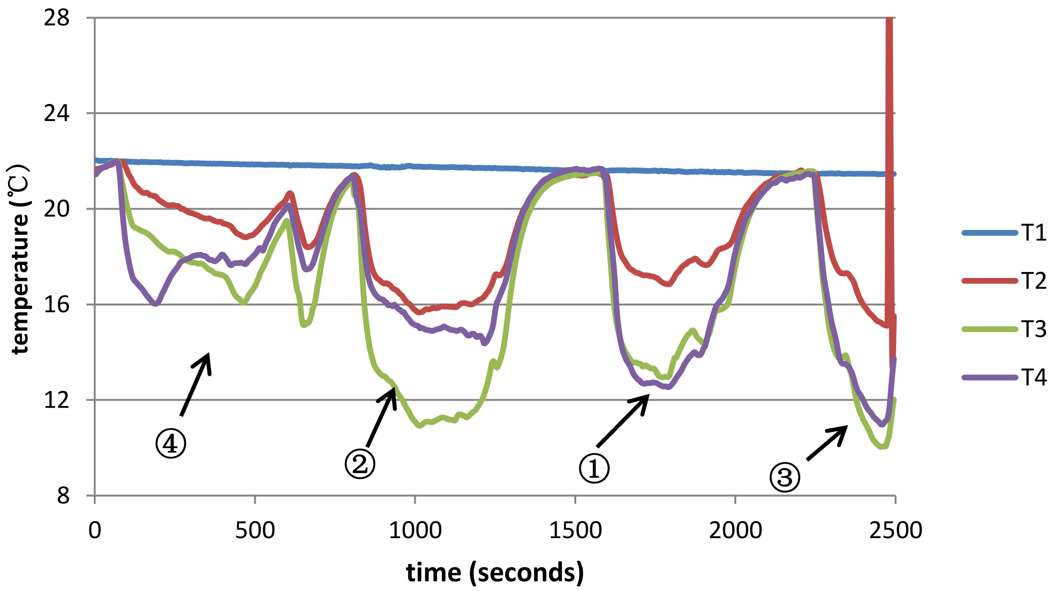


Figure 4.8 Temperature against time graph for B4

4.3. Set C experiments: Perspex model building above ground water

4.3.1. C1: 24h baseline experiment with pump rate at 30 litre/min

In this experiment, there is no fixed trend of temperatures. At the beginning of the experiment, i.e. from 0min to 400min, the outlet temperature (T4) is higher than the inlet temperature (T2) which is indicating the model building is giving heat to the water. The block temperature (T3) is higher than the others and is consistent with summer condition. From 400min to 1000min, the inlet temperature (T2) is higher than the outlet temperature (T4) which is indicating the model building is absorbing heat. During this period, the building temperature is low and is consistent with winter condition. After 1000 min, the trend has reversed again. This experiment began on Friday afternoon and is finished on Saturday afternoon. The reason for the fluctuation is again because the heating system in the room. The heating is on and then is turned off and is on again. The result of this experiment is not as good as the result in experiment B1.

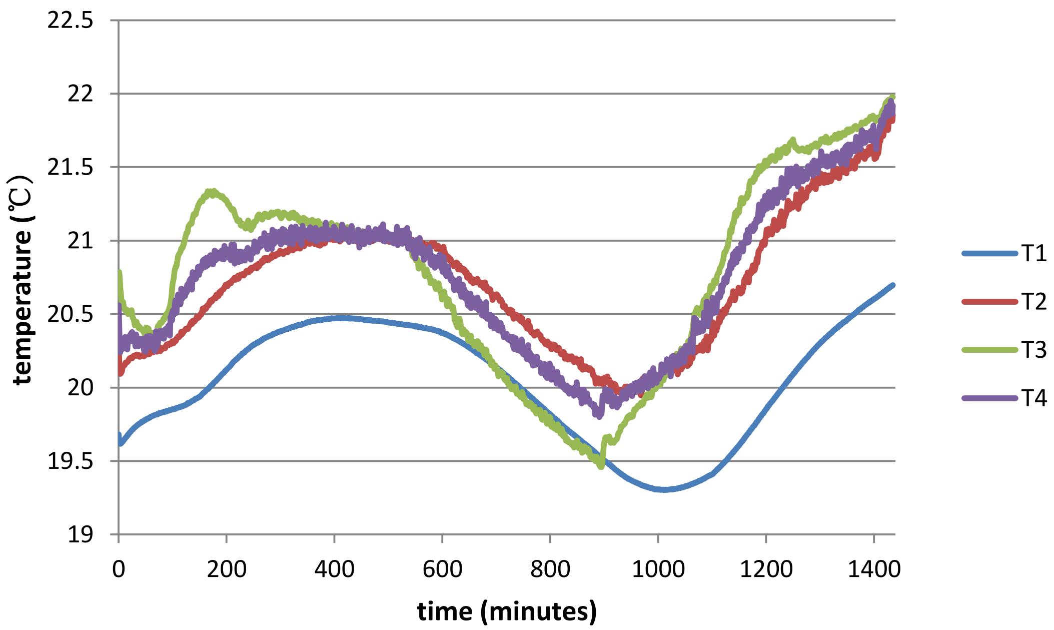


Figure 4.9 Temperature against time graph for C1

4.3.2. C2: 24h baseline experiment with heater at 20V

In this experiment, the outlet temperature (T4) is all the way higher than inlet temperature (T2) which is indicating heat is gained by water. There is no water flowing through the model building. It is the room temperature that is affecting the block temperature (T3) and indirectly affected the water temperature (T2 and T4) inside the building. The room has a higher temperature than the temperature of the block. Therefore, heat is transferred from the building to the water inside the building.

Comparing with the result in experiment B2, the two graphs (*Figure 4.6 and Figure 4.10)* is very similar. Although the two model building is made from different materials, they behave in the same way.

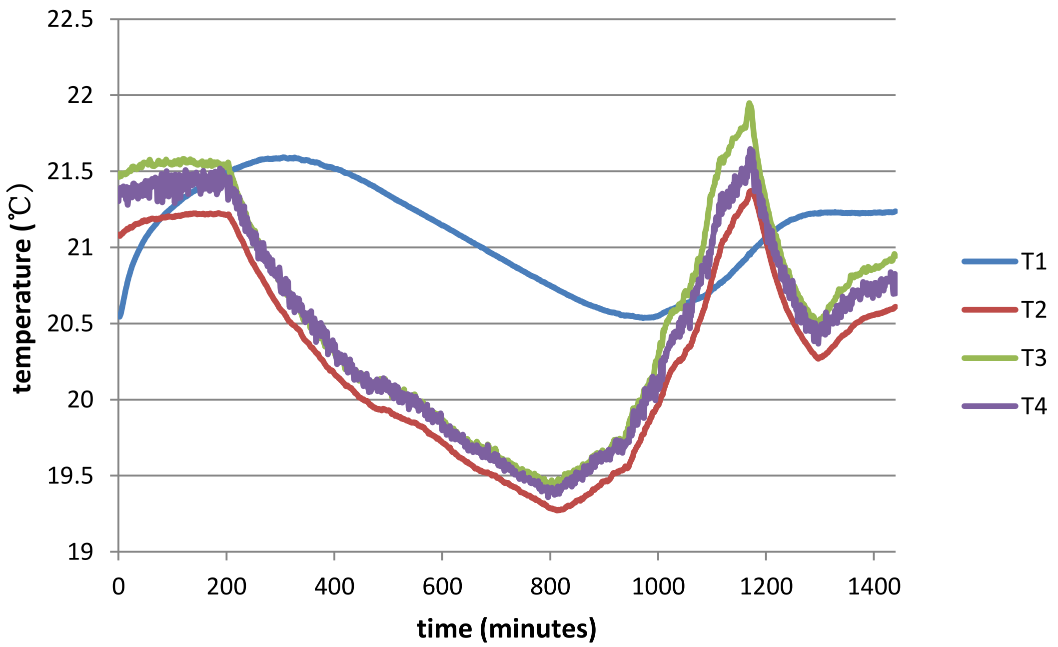


Figure 4.10 Temperature against time graph for C2

4.3.3. C3: 2h test with pump rate at 30 liter/min and heater at 30V

In this experiment, the outlet temperature (T4) is obviously higher than the inlet temperature (T2). Cooler ground water flows into model building and warmer ground water flows out of the building back into ground. Heat has been transferred from the hot building to cool water. The temperature of building is the highest among all temperatures. This is a very good model for summer time. Outside ambient air has a high temperature which leads to a hot building and water flows into the building to cool the building down.

Comparing to the result of experiment B3 in *Figure 4.7*, the trend of temperature is similar, C3 has shown a clearer result and the building has a higher temperature.

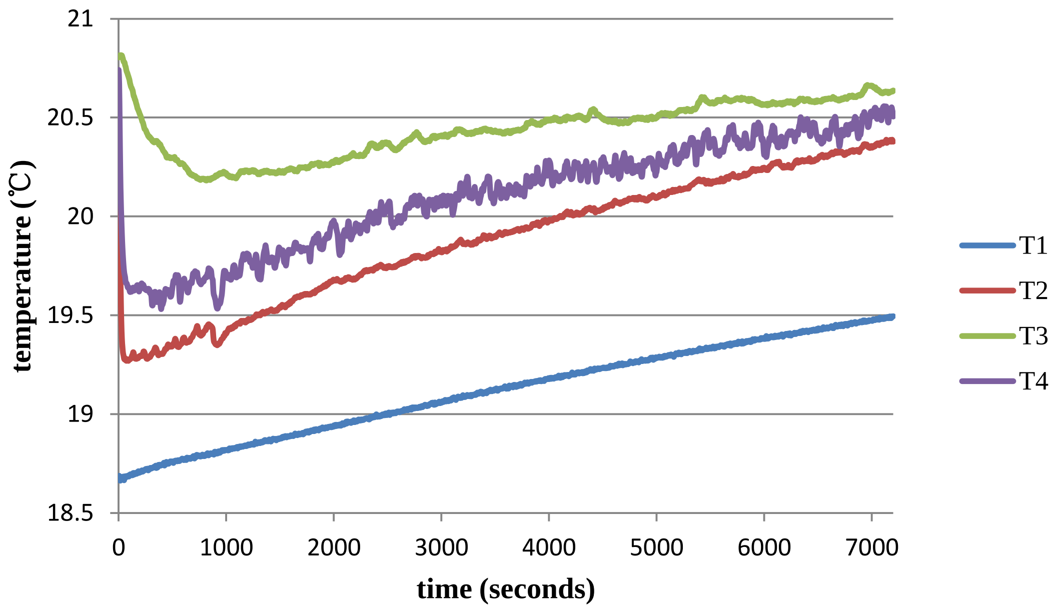


Figure 4.11 Temperature against time graph for C3

4.3.4. C4: Ice cube test with pump rate at 30 litre/min and heater at 30V

Again, this is an ice cube test in which ice cubes were added to the model building once the previous ice cubes have melted. This is the reason why there are two significant fluctuations in *Figure 4.12* which shows the overall results. The first fluctuation gives a good result. The inlet temperature (T2) is higher than the outlet temperature (T4). This is modeling winter time where the building is cold and warmer ground water flows in to heat the building up.

Comparing to the result in B4, the temperature variation is short period of time is not obvious. The reason for this is that Perspex has a much lower thermal conductivity than Al alloy.

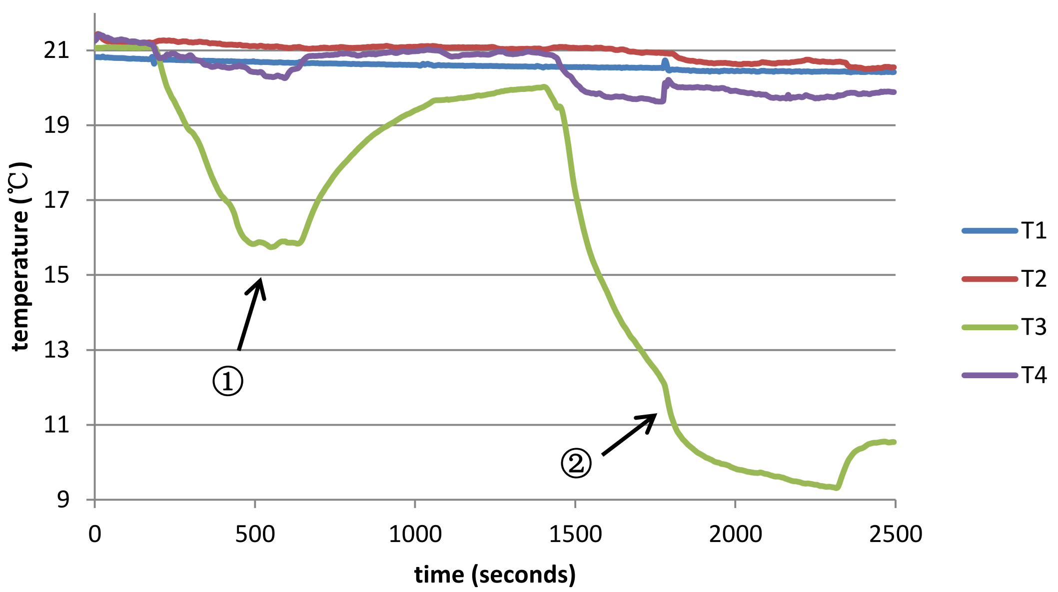


Figure 4.12 Temperature against time graph for C4

4.4. Pump rate correction factor

4.4.1. Theory

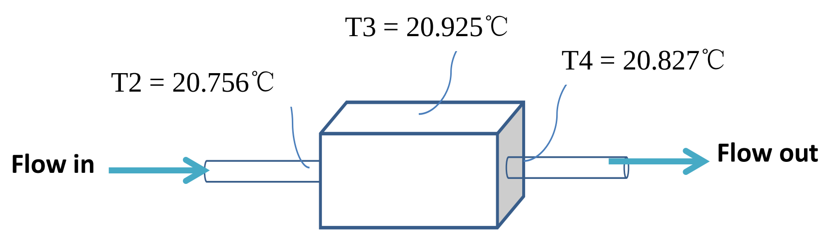
The theory behind these experiments is very simple. Only heat balance equation is used.

Heat transfer from water to block = Heat gain by the block + Heat loss to ambient air

The radiation heat loss to ambient air is expected to be very small compared to the main heat transfers, so it will be neglected in our calculation. First of all, a check of the heat balance equation is necessary. Taking experiment B1 as calculation example, other calculations are done in the same manner.

1. Assuming the water is not flowing at this instant

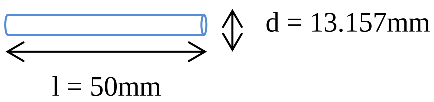
   At the instant of time = 450min,



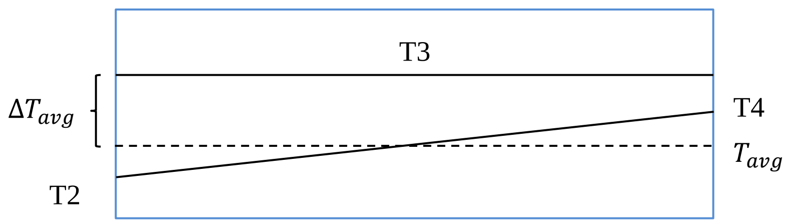
$$m_{block} = 0.15kg$$

$$S_{block} = 380\ J/kgK$$

$$S_{water} = 4200J/kgK$$



Temperature change:



At this instant, the average temperature change is:

$$\Delta T_{avg} = T3 - \frac{1}{2} \times (T2 + T4) = 20.925 - \frac{1}{2} \times (20.756 + 20.827) = 0.1335℃$$

Therefore, the heat transfers of model building:

$$Q_{block} = m_{block} \times S_{block} \times \Delta T_{avg} = 0.15kg \times \frac{380J}{kgK} \times 0.1335K = 7.6095J$$

The volume of water within the block at this instant: (Assume water is stationary)

$$V_{water} = \frac{1}{4} \times l \times \pi \times d^2 = \frac{1}{4} \times 50 \times 13.157^2 \times \pi = 6.80 \times 10^{-6} m^3$$

$$m_{water} = V_{water} \times \rho = 6.80 \times 10^{-6} m^3 \times \frac{1000kg}{m^3} = 6.80 \times 10^{-3} kg$$

The amount of heat that the block takes should be approximately the same as the amount of heat that water gives (ignoring radiation). Now check how much temperature would rise for this amount of heat:

$$Q_{water} = m_{water} \times S_{water} \times \Delta T_{avg} = 6.80 \times 10^{-3} kg \times \frac{4200J}{kgK} \times \Delta T = 7.6095J$$

$$\therefore \Delta \mathrm{T} = 0.26℃$$

$$\therefore \mathrm{T2} + \Delta \mathrm{T} = 21.02℃$$

This temperature is calculated assuming there is no water flow through the block. In reality, the water is flowing even just at one instant, and the temperature should be$\mathrm{T4} = 20.827℃$. The temperature is reasonably close the temperature predicted.

2. Now assuming the water within the block is actually flowing.

Take time = 450 min to 550 min, so $\Delta t = 100\text{min}$

Flow rate of pump = 0.3l/min

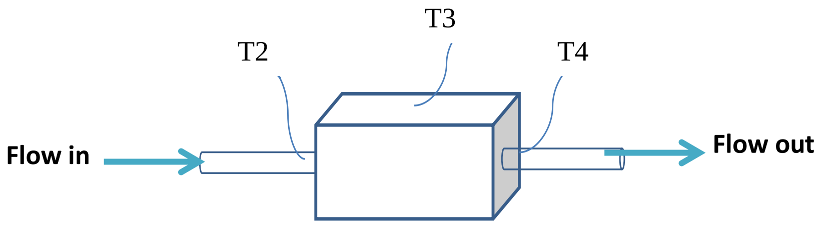


Table 4.1 temperature sum up for B1

	At 450min(℃)	**At 550min**(℃)	T_{avg} (℃)
T2	20.756	20.829	20.793
T4	20.827	20.893	20.860
T3	20.925	20.996	20.961

For block:

$$\Delta T_{block} = T3_{avg} - 0.5 \times (T2_{avg} + T4_{avg}) = 0.1345℃$$

Therefore, the heat transfer of block is:

$$Q_{block} = m_{block} \times S_{block} \times \Delta T_{blcok} = 0.15kg \times \frac{380J}{kgK} \times 0.1345K = 7.67J$$

For flowing water:

$$\Delta T_{water} = T4_{avg} - T2_{avg} = 0.067℃$$

$$m_{water} = 0.3l/\text{min} \times 100min \times 1000kg/m^3 = 30kg$$

Therefore, the heat transfer of water is:

$$Q_{water} = m_{water} \times S_{water} \times \Delta T_{water} = 30kg \times \frac{4200J}{kgK} \times 0.067 = 8442J$$

In theory, $Q_{water} \approx Q_{block}$. However, in this case, the value of Q_{water} is too large. The amount of water pumped through the building within 100min seems to be quite large. As mentioned in Section 4.3, the pump rate is a source of error. Although the flow meter was calibrated before, it is often found that air bubbles inside the flow path. This brought errors in measured flow rate. Occasionally, it is found that the flow rate is not at desired level even it is set correctly at the beginning of 24 hour test.

As an initial guess the flow rate has been decreased by a factor of 1000. Let's check the three experiment whether the pump rate is decreased by 1000 times. The same calculation method as above in the flowing water condition was used here. Using the value of inlet temperature (T2) and outlet temperature (T4), a value of model building temperature (T3) was deduced. Choosing the steady state in each experiment and calculate the theoretical value of T3 for each 100 minutes interval within the steady state. The calculation is done through Excel. A plot of theoretical T3 and real T3 will be produced. If the pump rate is indeed decreased by a factor of 100, the two lines will coincide.

4.4.2. Correction factor for experiment B

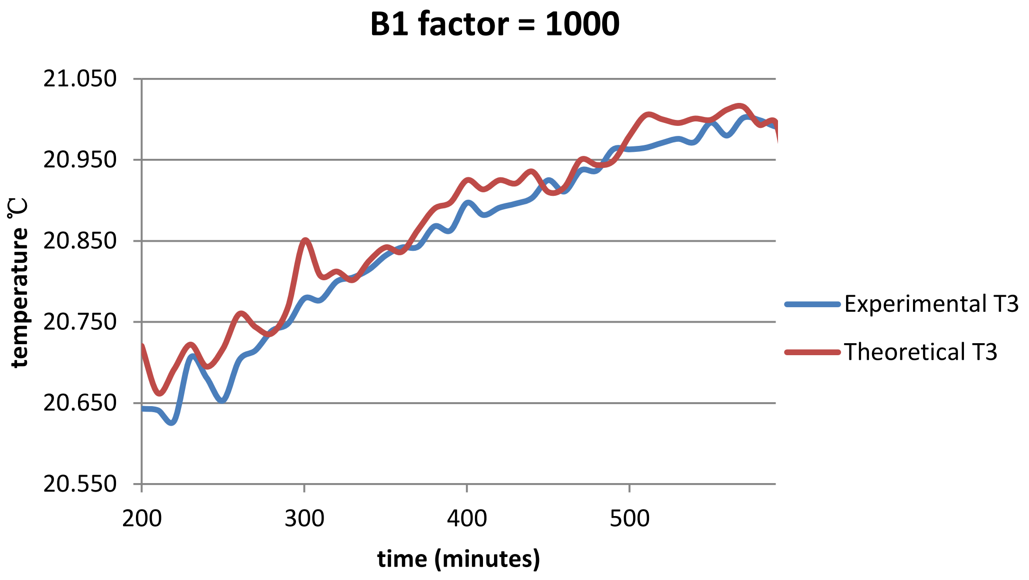


Figure 4.13 Theoretical T3 compare to Experimental T3 for B1

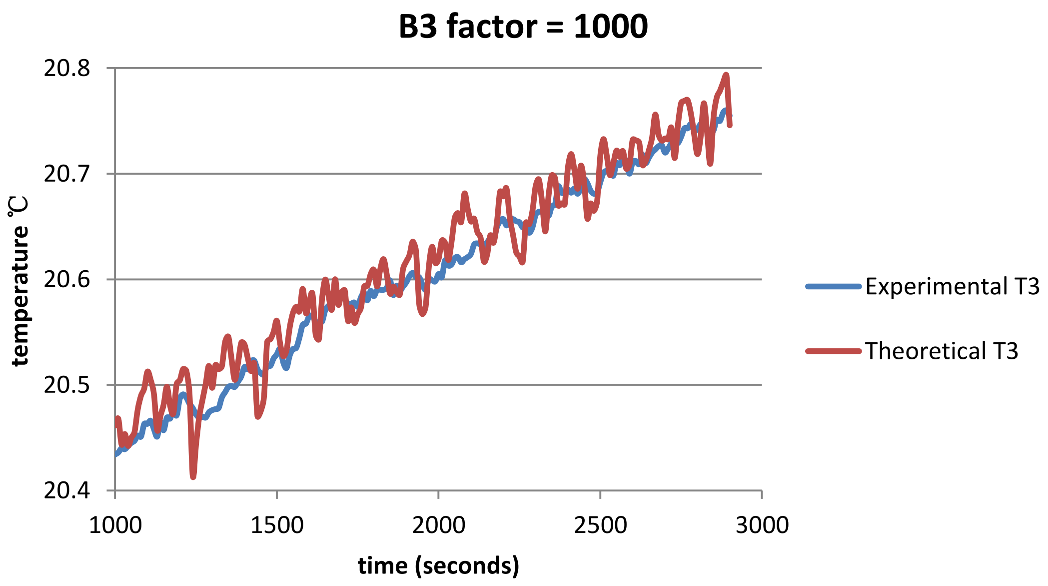


Figure 4.14 Theoretical T3 compare to Experimental T3 for B3

4.4.3. Correction factor for experiment C

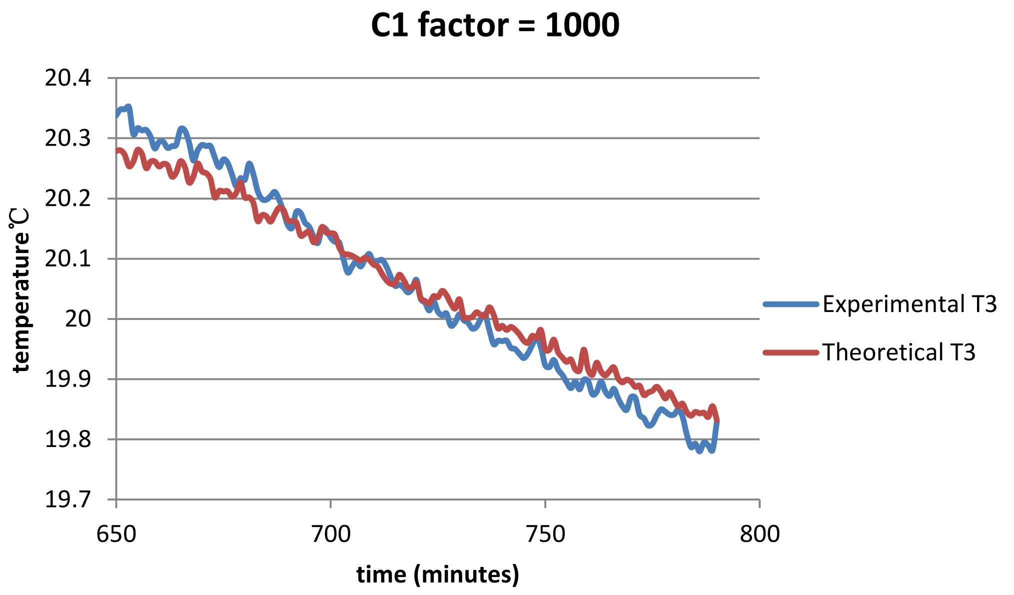


Figure 4.15 Theoretical T3 compare to Experimental T3 for C1

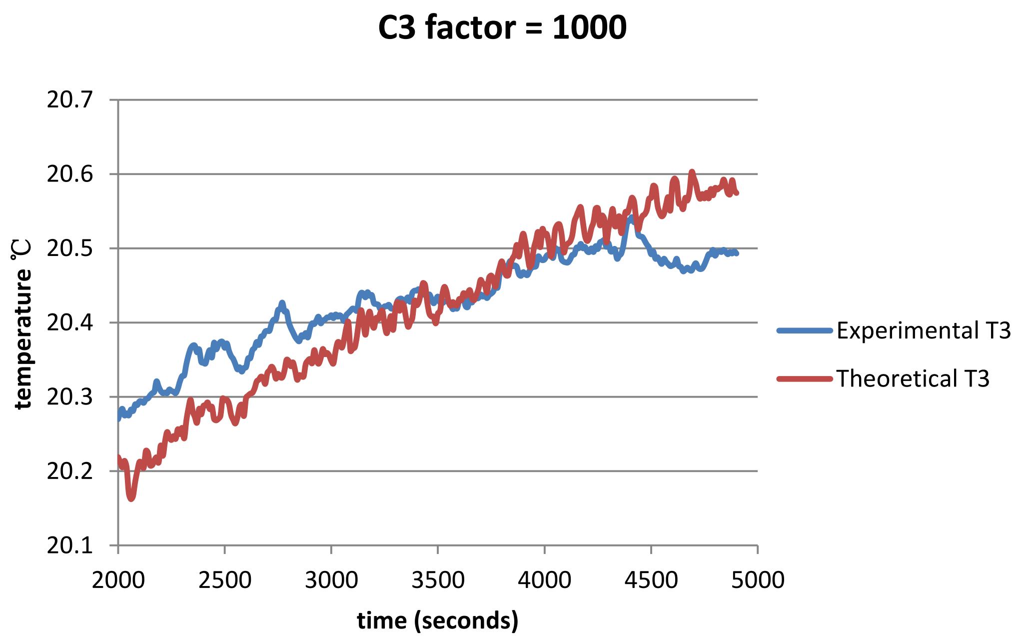


Figure 4.16 Theoretical T3 compare to Experimental T3 for C3

It is clearly shown in *Figure 4.13, Figure 4.14, Figure 4.15 and Figure 4.16* that the results of experimental T3 and theoretical T3 agree very well in experiment B and C. This is suggesting that the pump rate has been exaggerated by a factor of 1000.

The flow meter is pre-calibrated before installing onto the whole system. However, it still has a very large correction factor. Although care was taken to allow the air gaps to leave the system before the start of any experiment by sucking the air using needle tube, there still exist air gaps inside the pipe when water is circulating through the building. Air gaps could reduce water from circulating which decreases the flow rate significantly. It is always found in 24 hour experiment that the flow meter was reading 0.3l/min at the start of experiment. However, when inspected at the end of 24 hour experiment, the flow meter was reading some value below 0.3l/min nearly all the time. Occasionally, it was found that the flow meter is reading nothing while the pump is working at the right voltage.

Therefore, in further calculations, all flow rate in experiment B and C should be lowered by correction factor of 1000.

$$\text{flow rate} = \frac{0.3l/min}{correction\ factor} = 0.0003l/min \qquad [1]$$

4.4.4. Correction factor for experiment A

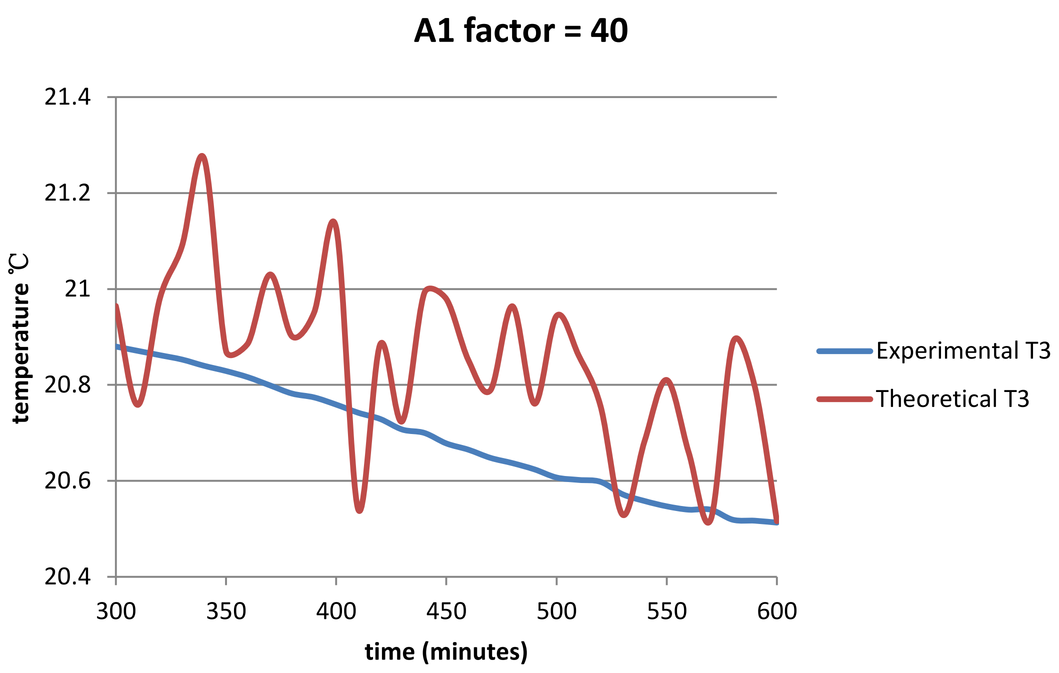


Figure 4.17 Theoretical T3 compare to Experimental T3 for A1

In experiment A1, it is shown in *Figure 4.17* that the value of theoretical T3 and real T3 do not agree well. The predicted theoretical T3 is fluctuating around real T3. This time, the correction factor is only 40. A possible explanation for this is pump is deteriorating with time. So at the beginning of the project, the flow meter/pump system is not so wrong and hence has a much smaller correction factor.

Therefore, pump rate in experiment A1 should be lowered by correction factor of 40. This is only a very rough estimation.

$$\text{flow rate} = \frac{0.3l/min}{correction\ factor} = 0.0075l/min \qquad [2]$$

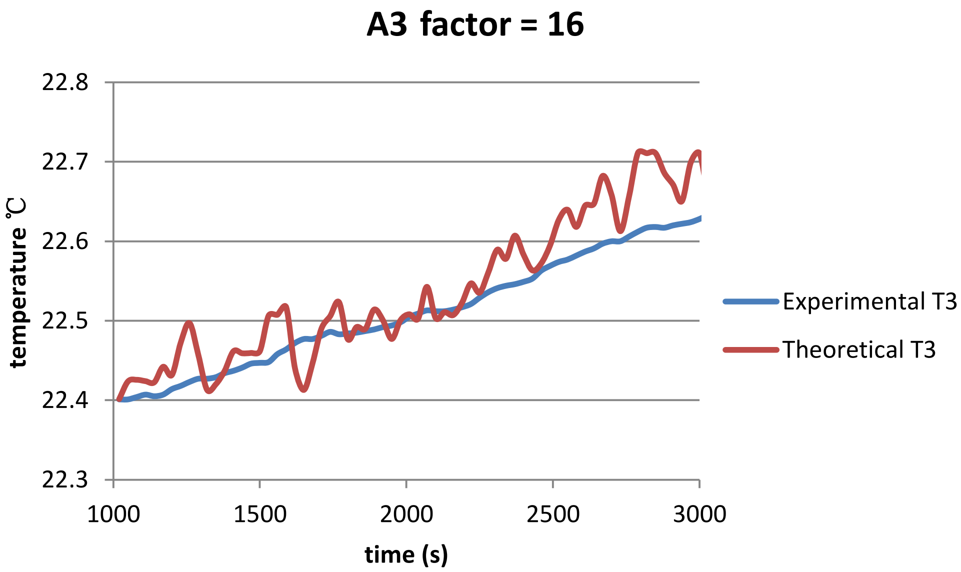


Figure 4.18 Theoretical T3 compare to Experimental T3 for A3

In experiment A3, it is shown in *Figure 4.18* that the value of theoretical T3 and real T3 agree well especially comparing to A1. The factor estimated is only 16 and is 2.5 times smaller than the factor in A1 and is 60 times smaller than the factor in experiment B and C. The explanation is again the pump is deteriorating with time and this is the very beginning of the project, so we are expecting a smaller correction factor.

Therefore, pump rate in experiment A3 should be lowered by correction factor of 16.

$$\text{flow rate} = \frac{0.3l/min}{correction\ factor} = 0.01875l/min \qquad [3]$$

4.5. Thermal conductivity of model building

Heat transfer occurs at a higher rate across materials of high thermal conductivity than across materials of low thermal conductivity. Materials with high thermal conductivity are widely used in heat sink application while materials with low thermal conductivity are used as thermal insulation.

The effect of temperature on thermal conductivity is different for metals and nonmetals. In metals conductivity is primarily due to free electrons. Following Wiedemann–Franz law thermal conductivity of metals is approximately proportional to the absolute temperature (in Kelvin) times electrical conductivity. In pure metals the electrical conductivity decreases with increasing temperature and thus the product of the two, the thermal conductivity stays approximately constant. In alloys the change in electrical conductivity is usually smaller and thus thermal conductivity increases with temperature, often proportional to temperature.

On the other hand, heat conductivity in nonmetals is mainly due to lattice vibrations (phonons). Except for high quality crystals at low temperatures, the phonon mean free path is not reduced significantly at higher temperatures. Thus the thermal conductivity of nonmetals is approximately constant at low temperatures. [2]

Under steady-state conditions the heat flow Q [in W] that conducts through a single material is:

- Proportional to the temperature difference $(T_i - T_o)$ across the element;
- Inversely proportional to the thickness of the element
- In construction industry, the value of R-value (thermal resistance) and U-value (thermal transmittance) are usually used. The two values are reciprocal to each other and both are dependent on the thickness of material. U-value signifies the thermal conductivity per unit area of the material.

[2] Definitions from Wikipedia

These leads to the steady-state heat conduction equation:

$$Q = \frac{\lambda \times A}{d}(T_i - T_o) = UA\Delta T \qquad [4]$$

Where d is the thickness of the material [in m] and A is its surface area [in m^2]. The proportionality constant λ is the thermal conductivity, a property of the material. It is clear from the equation that the units of λ must be [W/mK], and heat flow is constant through the material layer. The following table summarizes these terms.

Table 4.2 Terms describing thermal behavior of materials

Symbol	**Parameter**	**Unit**	**Calculation**
λ	Thermal conductivity	W/mK	
U-value	Thermal transmittance	W/m^2K	λ/d
R-value	Thermal resistance	m^2K/W	d/λ
K	Overall thermal conductance of a component (network conductance)	W/K	UA or $\lambda\mathrm{A}/\mathrm{d}$
R	Overall thermal resistance of a component (network resistance)	K/W	1/K or $\mathrm{d}/\lambda\mathrm{A}$
d	Thickness of the material	m	Given
A	Area of material	m^2	given

As shown in section 4.4 that in experiment A, only A3 has a good correction factor ready to use in calculation. In experiment B and C, correction factors are in consistent.

In later sections, calculations for thermal conductivity in each three experiments will be carried out. In theory, the value obtained in experiment A and B should be the same as the same material (Al-alloy) is used to make model building. The values for experiment A and B should be much higher than the value calculated for experiment C as Perspex is no doubt a low thermal conductivity material.

4.5.1. Thermal conductivity for A3

Take time = 6000s to 6600 min, so $\Delta t = 10\text{min}$

Flow rate of pump = 0.3l/min/16 = 0.01875l/min

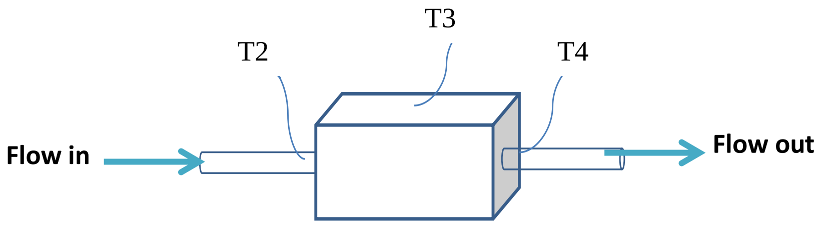


Table 4.3 temperature sum up for A3

	At 6000s(℃)	**At 6600min**(℃)	T_{avg} (℃)
T2	22.653	22.667	22.66
T4	22.673	22.699	22.686
T3	22.911	22.95	22.9305

For flowing water:

$$\Delta T_{water} = T4_{avg} - T2_{avg} = 0.026℃$$

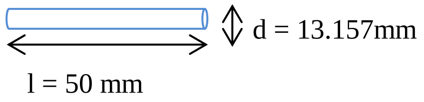
$$m_{water} = 0.01875l/\text{min} \times 10min \times 1000kg/m^3 = 0.1875kg$$

Therefore, the heat transfer of water is:

$$Q_{water} = m_{water} \times S_{water} \times \Delta T_{water} = 0.1875kg \times \frac{4200J}{kgK} \times 0.026 = 20.475J$$

For block:

$$\Delta T_{block} = T3_{avg} - 0.5 \times (T2_{avg} + T4_{avg}) = 0.2575℃$$



Area of contacting flowing ground water:

$$A = \pi \times d \times l = \pi \times 50 \times 13.157 = 2.067 \times 10^{-3} m^2$$

Therefore, the U-value of the Al-alloy model building:

$$U = \frac{Q}{A \times \Delta T} = \frac{20.475 J/10 min}{2.067 \times 10^{-3} m^2 \times 0.2575 K} = 64.1\ W/m^2 K$$

The thermal conductivity is:

$$\lambda = U \times d = 64.1 \times 0.05 = 3.206\ \mathrm{W/mK}$$

However, the thermal conductivity for Al-alloy is 164W/mK and the calculated value is too small compared to theoretical value. This is suggesting that experiment A is not really working well in terms of interpreting thermal conductivity.

4.5.2. Thermal conductivity for B1

Take time = 450 min to 550 min, so $\Delta t = 100\text{min}$

Flow rate of pump = 0.3l/min/1000 = 0.0003l/min

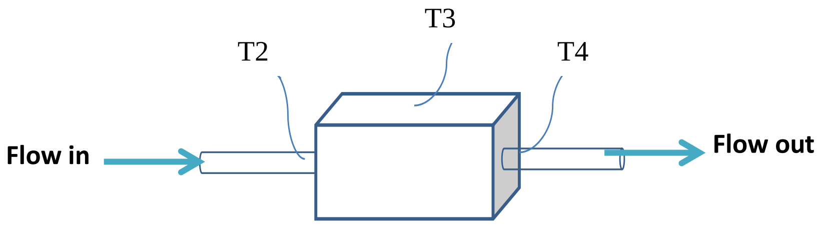


Table 4.3 temperature sum up for B1

	At 450min(℃)	**At 550min**(℃)	T_{avg} (℃)
T2	20.756	20.829	20.793
T4	20.827	20.893	20.860
T3	20.925	20.996	20.961

For flowing water:

$$\Delta T_{water} = T4_{avg} - T2_{avg} = 0.067℃$$

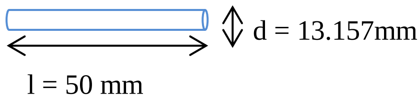
$$m_{water} = 0.0003l/\text{min} \times 100min \times 1000kg/m^3 = 0.03kg$$

Therefore, the heat transfer of water is:

$$Q_{water} = m_{water} \times S_{water} \times \Delta T_{water} = 0.03kg \times \frac{4200J}{kgK} \times 0.067K = 8.442J$$

For block:

$$\Delta T_{block} = T3_{avg} - 0.5 \times (T2_{avg} + T4_{avg}) = 0.1345℃$$



Area of contacting flowing ground water:

$$\mathrm{A} = \pi \times \mathrm{d} \times \mathrm{l} = \pi \times 50 \times 13.157 = 2.067 \times 10^{-3} m^2$$

Therefore, the U-value of the Al-alloy model building:

$$\mathrm{U} = \frac{Q}{A \times \Delta T} = \frac{8.442 J/100 min}{2.067 \times 10^{-3} m^2 \times 0.1345 K} = 5.062\ W/m^2 K$$

The thermal conductivity is:

$$\lambda = \mathrm{U} \times \mathrm{d} = 5.062 \times 0.05 = 0.253\ \mathrm{W/mK}$$

However, the thermal conductivity for Al-alloy is 164W/mK and the calculated value is again too small compared to theoretical value. This is suggesting that experiment B is not really working well in terms of interpreting thermal conductivity. As a result, experiment A and B did not give a good interpretation for thermal conductivity.

4.5.3. Thermal conductivity for C1

Take time = 700 min to 800 min, so $\Delta t = 100\text{min}$

Flow rate of pump = 0.3l/min/1000 = 0.0003l/min

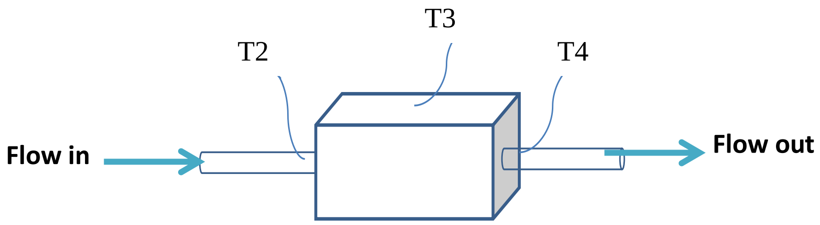


Table 4.4 temperature sum up for C1

	At 700min(℃)	**At 800min**(℃)	T_{avg} (℃)
T2	20.635	20.297	20.466
T4	20.456	20.071	20.264
T3	20.135	19.795	19.965

For flowing water:

$$\Delta T_{water} = T2_{avg} - T4_{avg} = 0.202℃$$

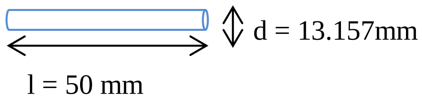
$$m_{water} = 0.0003l/\text{min} \times 100min \times 1000kg/m^3 = 0.03kg$$

Therefore, the heat transfer of water is:

$$Q_{water} = m_{water} \times S_{water} \times \Delta T_{water} = 0.03kg \times \frac{4200J}{kgK} \times 0.202 = 25.45J$$

For block:

$$\Delta T_{block} = 0.5 \times (T2_{avg} + T4_{avg}) - T3_{avg} = 0.4℃$$



Area of contacting flowing ground water:

$$A = \pi \times d \times l = \pi \times 50 \times 13.157 = 2.067 \times 10^{-3} m^2$$

Therefore, the U-value of the Perspex model building:

$$U = \frac{Q}{A \times \Delta T} = \frac{25.45J/100min}{2.067 * 10^{-3} m^2 * 0.4K} = 5.13\ W/m^2K$$

The thermal conductivity is:

$$\lambda = U \times d = 5.13 \times 0.05 = 0.257\ \mathrm{W/mK}$$

The thermal conductivity for Perspex is 0.25W/mK which is very close to what is interpreted from the graph. Unlike the calculation for experiment A and B for metal model building, thermal conductivity for experiment C agrees very well to theoretical value with only 2.8% percentage error. Hence it can be concluded that experiment C is very successful.

5. Conclusions and Future Work

5.1. Conclusions

5.1.1. Sub-experiments under each set

The first experiment in each set is a base line test with pump operating solo. The second experiment is each set is another base line test with heater on solo. These two tests are running on a 24 hour base and the temperature in the room (ambient temperature) has significant influence on the results.

The third experiment with heater and pump working together, successfully modeled the summer time condition. In this condition, cooler ground water flows into model building and warmer ground water flows out of the building back into ground. Heat has been transferred from the hot building to cool water.

The fourth experiment with heater and pump working together and uses ice cubes to cool the building down, is a successful model for winter condition. This means the warmer ground water flows into the building and heat has been transferred from water to the building and hence cooler ground water flows out from the building.

5.1.2. Different set experiments

Experiment A is designed to have the model building partly sunken in the ground water and therefore the behavior of inlet/outlet temperatures and temperature of model building itself are largely affected by the temperature of ground water. As a result, this set of experiment does not give very clear results.

Experiment B and C are having a model building separated from ground water. This enables the inlet/outlet temperatures and temperature of model building itself are only affected by the ambient air. These two experiments give better results than experiment A.

5.1.3. Flow rate correction factor

Experiment B and C have flow rate correction factor of 1000 which means in each case, the flow rate should be decreased by 1000 times. The back calculation of theoretical T3 and experiment T3 agree very well. Although the flow meter was calibrated before, it is often found that air bubbles inside the flow path. This brought errors in measured flow rate.

However, in experiment A, the correction factor is not fixed and it is much smaller than in experiment B and C. The explanation is the pump is deteriorating with time and this is the very beginning of the project, so we are expecting a smaller correction factor.

5.1.4. Thermal conductivity

The interpretation of thermal conductivity from graphs is good from Perspex model building with a percentage error only 2.8%. However, the calculated values for Al-alloy model building are not right for both experiment A and B. This is suggesting that the experiments designed only works for Perspex model building in terms of interpretation of thermal conductivity.

5.2. Future work

- Use different materials and different dimensions for the model building
- Design different tests to achieve right value of thermal conductivity for metals
- Design circulation of water flow within the building

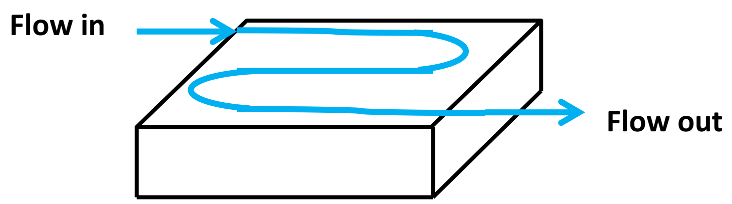


Figure 5.1 illustration of circulation of water flow within the building

Acknowledgement

The author would like to thank all the Geotechnical laboratory staff at CUED for the technical assistance given during the preparation of experiments. Special thanks go to Dr. Madabhushi and Mr. Chris Knight for all the kind help and great support

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Appendix

Risk Assessment

The risk assessment was submitted in Michaelmas term. It was assessed to be accurate. Since this project does not involve any hazard, no particular caution needed to be take care of. If one were to perform this project again, the same level of safety measures should be taken.