EXPERIMENTAL INVESTIGATION ON THE CONDENSATION EFFICIENCY OF HUMID AIR OVER CYLINDER AND FLAT PLATE CONDENSERS

by
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ABSTRACT

EXPERIMENTAL INVESTIGATION ON THE CONDENSATION EFFICIENCY OF HUMID AIR OVER A CYLINDER AND A FLAT PLATE CONDENSER

The condensation efficiency of humid air over surfaces which are cooled by water were investigated experimentally by using the Condensation Test Facility (CTF) in Yeditepe University laboratory. The condensation efficiency of a condenser can be defined as the ratio of heat released during the condensation process to the total heat extracted from the mixture of vapor and non-condensable gas (ratio of latent heat to total heat). The present study employed two cooling surfaces, namely, a cylinder and a flat plate, which were designed to provide constant temperature boundary conditions. The condensation efficiencies of cross flows over two cooling surfaces were separately examined as a function of process air temperature, flow rate of the process air, relative humidity and cooling water temperature. The present study employed two cooling surfaces, namely, a cylinder and a flat plate, which were designed to provide constant temperature boundary conditions. The condensation efficiencies of cross flows over two cooling surfaces were separately examined as a function of process air temperature, flow rate of the process air, relative humidity and cooling water temperature. The condensation efficiency was observed to increase in both condensers as process air humidity increases. For the case of flat plate condenser, condensation efficiency was observed to increase as cooling water temperature increases.

ÖZET

SİLİNDİR VE DÜZ TABAKA KONDENSER ÜZERİNDE NEMLİ HAVA YOĞUŞMA VERİMLİLİĞİ ÜZERİNE DENEYSEL İNCELEME

Nemli havanın, su ile soğutulan yüzeyler üzerindeki yoğuşma verimliliği, Yeditepe Üniversitesi laboratuvarında bulunan Yoğuşma Test Tesisi (CTF) kullanılarak deneysel olarak incelenmiştir. Bir kondenser yoğuşma verimliliği, yoğuşma işlemi sırasında salınan ısının, buhar ve yoğuşamayan gaz karışımından çıkarılan toplam ısıya oranı (gizli ısının toplam ısıya oranı) olarak tanımlanabilir. Mevcut CTF, hava soğutmalı bir çapraz akışlı kondenser için tasarlandığından, sabit sıcaklık sınır koşullarında yoğuşma yüzeyleri sağlayacak şekilde modifiye edilmiştir. Sonrasında, yoğuşma verimi, bir işlem tüpü ve işlem havasının akış hızı, bağıl nem ve soğutma suyu sıcaklığının bir fonksiyonu olarak bir silindir ve düz bir plaka üzerindeki çapraz akışlar için incelenmiştir. İki kondenserde de yoğuşma verimliliğinin bağıl nem oranı ile doğru orantıda arttığı gözlemlenmiştir. Düz plaka kondenserde, soğutma suyu sıcaklığının artmasıyla yoğuşma verimliliğinin arttığı gözlemlenmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

η	Efficiency
ΔT_m	Mean temperature difference
Φ	Relative humidity
A	Area
Q	Heat transfer rate
U	Overall heat transfer coefficient
Cp	Specific heat
Exp	Experiment
h_{fg}	Enthalpy of vaporization
LMTD	Logarithmic mean temperature difference
$\dot{m}_l$	Condensation rate
$\dot{m}_w$	Water flow rate
PLC	Programmable logic controller
T_1	Inlet water temperature
T_2	Outlet water temperature

1. INTRODUCTION

1.1. BASICS OF CONDENSATION

Condensation happens when the vapor temperature drops below its temperature of saturation. Fundamental work on condensation was done by Wilhelm Nusselt in order to reduce the condensation process complexity to a more straightforward model. According to Nusselt's work, resistance to the heat release during condensation takes place in the condensate film [1]. This is generally performed by contacting the vapor with a solid surface that is below the saturation temperature of vapor. However, condensation also occurs on the free surface of a liquid or in a gas when the surface temperature of the liquid or the gas to which vapor is exposed is below saturation temperature. In the last mentioned form, liquid droplets caused by the condensation process, form a fog in the vapor.

Two different modes of condensation, which are drop wise and film condensations, can be observed during condensation process. During film condensation mode, the condensate causes a liquid film on the cooling surface of the solid, and the condensate slides down due to the gravitational force. The thickness of the formed liquid film increases further down the flow direction since more vapor condense over the solid surface. On the other hand, during drop wise condensation, the condensate forms droplets on the surface, resulting that the solid surface is covered by droplets instead of condensate film.

During film condensation, surface area of the solid is covered by a liquid layer with increased thickness due to buildup of the condensate. Creation of this liquid film serves as an insulation to heat transfer between the vapor and solid surface. The heat of vaporization released by the condensed vapor, has to pass this liquid insulation layer prior to reaching the surface. In dropwise condensation, the droplets formed by the condensate move down as they reach a certain size, therefore clearing the solid surface. This process exposes vapor directly to the cold surface without any barriers as in film wise condensation. Since the insulation layer of built up condensate is non-existent, heat transfer rates are larger in drop wise condensation. Due to this higher heat transfer rate, the dropwise condensation method is preferred for condensation applications. Dropwise condensation can be obtained by employing various vapor additives and surface coatings but these effects are considered temporary. Because of this, the assumption of the film wise condensation is employed during the design process of condensation heat transfer equipment [2].

2. LITERATURE SURVEY

The early work by A.P. Colburn and O.A. Hougen [3] states the importance of condensation phenomenon of the vapor mixture and non-condensing gas while designing condensers. Another work on the subject of vapor and non-condensing gas were experimented by Sparrow and Lin [4] which concludes that existence of a very little amount of non-condensable gas inside vapor may cause a large buildup of the non-condensable at the liquid-vapor interface therefore reducing heat transfer rates well over fifty percent. On another research, it was shown that small amount concentrations of the non-condensable gas may have a large effect on the heat transfer rate [5]. This decline of the heat transfer rate was caused mainly due to the gas-vapor boundary layers diffusional resistance. The interfacial resistance between the mixture and the liquid film was shown to have less effect on the heat transfer rate.

In flat plate condensers, heat transfer rates of dropwise condensation were much higher than film condensation rates in the presence of pure steam. But in the presence of air both dropwise and film condensations showed similar heat transfer rates during condensation processes [6]. Experimental work showed that, in a water-cooled flat plate condenser, rate of heat transfer decreased as the angle of the plate condenser to the horizontal became smaller. As the concentration of non-condensable air increased, heat transfer rate decreased. Results showed that in a pure steam environment heat transfer rates were higher for an upward facing plate in comparison to a downward facing condenser. In a system where air was present, on the other hand, this trend was reversed [7].

The angle of inclinations effect in the flat-plate condenser on laminar film condensation was analytically studied by Siow and Ormiston. It was concluded that liquid film became thinner as the angle of inclination increased while local Nusselt number stayed fairly constant [8].

In their study on condensation in the presence of non-condensable gas, Wang and Tu found that the main reason behind reduction of the heat transfer rate was due to the diffusional resistance of boundary layer between gas and vapor and this reduction was more prominent in low pressure, low Reynolds number mixtures. Resistance among the condensate liquid film and the air-steam mixture was proven to be a smaller effect on heat transfer rate [9].

Pandey experimentally confirmed that heat flux in dropwise condensation mode is higher than in film wise condensation mode in atmospheric pressure setting. This was explained by how condensate is formed on the cooling surface. During dropwise condensation, vapor drops are separate on the condenser surface and the drops are continually released as new drops are formed on the surface exposed to vapor. In film condensation, condensate covers the surface of the condenser, thus lowering heat flux [10].

In analytical modelling of laminar film condensation, it was found that the effect of vapor shear stress on heat transfer coefficient was significant up to several folds in lower Reynolds numbers. This effect decreased with increasing Reynolds number where the effect of vapor shear stress was insignificant at around Re=10000 [11].

Ahn et al. [12] performed an experimental work on the condensation efficiency of humid air on a cross-flow flat-plate condenser in which, air was used as the cooling liquid. The most important result was that increase in cooling air flow rate caused decrease in efficiency of condensation. The results also yield that the efficiency increased as the humidity of air-steam mixture increased with both air-steam mixture flow rate and cooling air flow rate kept constant, the effect of steam-air mixture flow rate was found to have little effect on the efficiency.

The present study is an extension of the study by Ahn et al. [12]. With the purpose of providing the constant temperature boundary condition at the cooling surface, the present study employs water as a cooling fluid instead of air used in the cross-flow condenser [12]. The present study aim to investigate the condensation efficiency of cross flows of humid air over both a cylinder (inside which cooling water flows) and a flat surface (under which cooling water flows).

3. THEORY

Condensation efficiency that is defined by the rate of heat extracted during the condensation to the total heat released from the mixture of vapor and non-condensable gas. Condensation efficiency measures how efficiently the system can condense the vapor for a given heat transfer rate accessible in the system. Efficiency of condensation (η) can be shown as follows.

$$\eta = \frac{(\dot{m}_l h_{fg})}{Q} \tag{3.1}$$

When condensation of pure vapor occurs at the temperature of saturation, efficiency of condensation is 100 percent if the condensate remains at the temperature of saturation. Whereas the condensation of vapor in the presence of non-condensing gas results in an efficiency value of less than 100 percent. In this study, the purpose is understanding how efficiently vapor can be condensed from the system with respect to the energy consumption.

In the present study the following equations are considered.

$$Q = \dot{m}_w C_p (T_2 - T_1) \tag{3.2}$$

$$\Delta Tm = \frac{(T_{air_i} - T_1) - (T_{air_o} - T_2)}{ln(T_{air_i} - T_1) - ln(T_{air_o} - T_2)} \tag{3.3}$$

$$U = \frac{Q}{A \Delta Tm} \tag{3.4}$$

Where;

$\dot{m}_l$ Condensation rate [kg/s].

$\dot{m}_w$ Water flow rate through the pipe or plate condenser [kg/s].

T_{air_i} Process air temperature at inlet [°C].

T_{air_o} Process air temperature at outlet [°C].

T_1 Water temperature at the inlet of the pipe and plate condenser [°C].

T_2 Water temperature at the exit of the pipe and plate condenser [°C].

C_p Specific heat of water at the average temperature of inlet and exit [J/kg°C].

Q Heat transfer from air to water [W].

h_{fg} Enthalpy of vaporization [J/kg].

η Condensation efficiency.

A Outer surface of the condenser exposed to air-steam mixture.

ΔT_m Mean temperature difference between water and process air.

U Heat transfer coefficient among water flow and process air based on A [W/m^{2}K].

4. EXPERIMENTAL SETUP

The present experimental setup includes Condensation Test Facility (CTF), a water tower, a double relay thermostat, a DC water pump, two resistance heaters (above and below the test section), water heater, heat exchanger, electronic scale and two power supplies for both water pump and resistance heaters. These are discussed in detail as below.

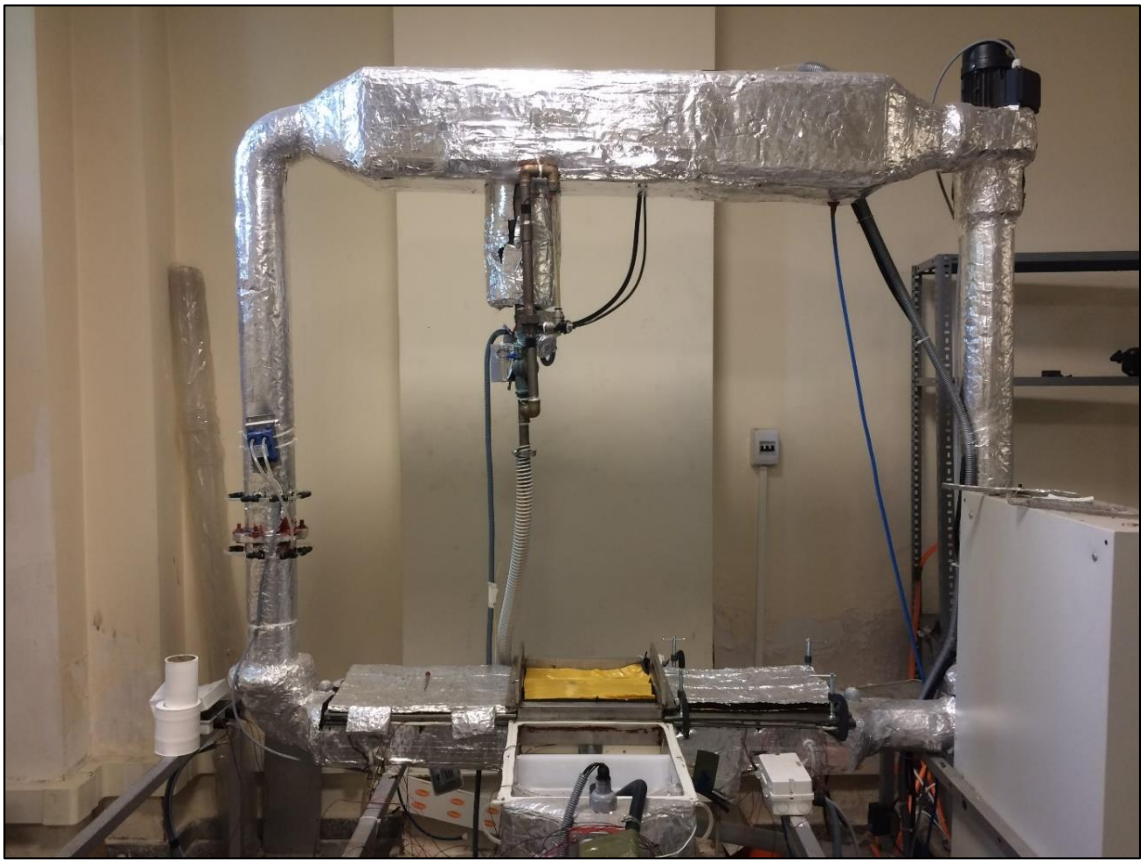

Figure 4.1. The CTF setup

The CTF setup is inclined 0.5º to the horizontal to make condensate flow easy over the cooling surface. CTF consists of a 24V AC fan, a 1000 W boiler, an orifice flow meter for flow measurement, two resistance heaters in the top middle part, dry-wet bulb thermocouples for humidity measurement, and the test section in the middle as it can be seen in Figure 4.1. Condensation test facility is completely isolated and automatically controlled by the PLC (Programmable Logic Controller). The test section can easily be modified, depending on cooling surface geometries.

Air-steam mixture is in a closed cycle in the CTF. The temperature of the mixture is controlled by three electrical heaters whose total power is 3300 W. The humidity of the mixture is controlled by adjusting heater power in the water boiler. Cooling water flow rate and air-steam mixture flow rate were kept constant during experiments, and data were taken when the system reached a steady state. During experiments, CTF was capable of keeping the temperature of inlet air-steam mixture between ±0.2°C and the relative humidity at around ±0.5 percent.

Figure 4.2. Water tower

The cooling water cycle is also a closed cycle in the present setup. A DC pump supplies water to an inner tank inside a larger tank in order to keep the water head at the same level. The cooling water flows from the bottom of the inner tank to the cooling condenser in the test section by the water head above the cooling surface in the test section. The water head can be adjusted between 0-100 cm according to the desired flow rate to the condenser. Excess water flows out of the inner tank to the large tank, and excess water flows back into the heating tank to be reused. The temperature of the cooling water is controlled by a double relay thermostat and its thermocouple is placed inside the inner tank which can be seen in Figure 4.2.

A double relay thermostat was used to control the cooling water temperature to a desired value as seen in Figure 4.3. Working temperature interval is between -50°C and 99°C. During experiments, the thermostat was able to keep cooling water temperature at ± 0.5°C within a set value.

Figure 4.3. Double relay thermostat

1500W electrical resistance heater was used to heat water according to thermostat input. Resistance heater was able to heat water up to 30°C in around 20 minutes as it cycled.

Figure 4.4. Heat exchanger for the cooling process of water

Resistance heaters were placed both on the top and bottom of the test section to reduce condensation at the Plexiglas covers of the test section.

A 12V eight by eight fan was used to cool water as it cycles during experiments which can be seen in Figure 4.4.

A 24V DC 1.7A water pump capable of pumping 3.8L/m was used in the water cycle to pump heated water in to the water tank as seen in Figure 4.5.

Figure 4.5. Water pump used in the experiments

The condensate mass flow rate was measured by employing an electric scale that can weigh up to six kilograms with the resolution of 0.01g. The electronic scale delivers data every second to the computer via RS-232 cable.

Water and steam-air mixture flow can be seen in Figure 4.6 and whole experiments setup can be seen in Figure 4.7.

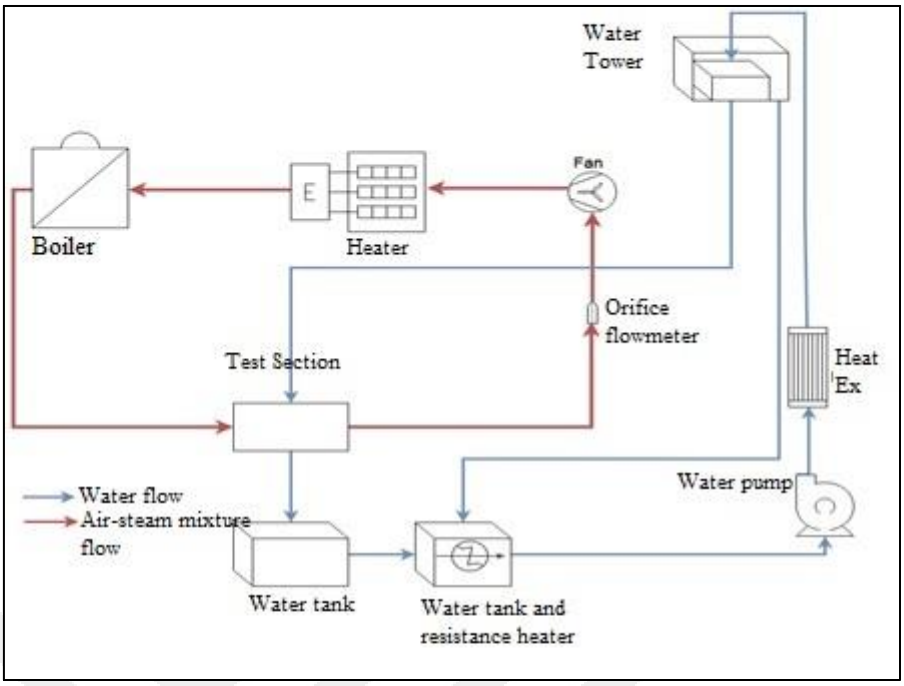

Figure 4.6. Complete experimental setup scheme

Figure 4.7. Complete experimental setup

5. TEST SECTION

5.1. CYLINDRICAL CONDENSER

Cylindrical condenser made of aluminum with 20 mm in diameter and 200 mm in length was used for experiments. Inlet thermocouple was placed at the base of the aluminum where it was insulated from the test section and outlet thermocouple was placed inside a mix-box in order to obtain better average temperature values at the exit. Exit and inlet parts were completely insulated as seen in Figure 5.1. Plastic parts were sealed with heat and water resistant silicone in order to prevent condensate leaks.

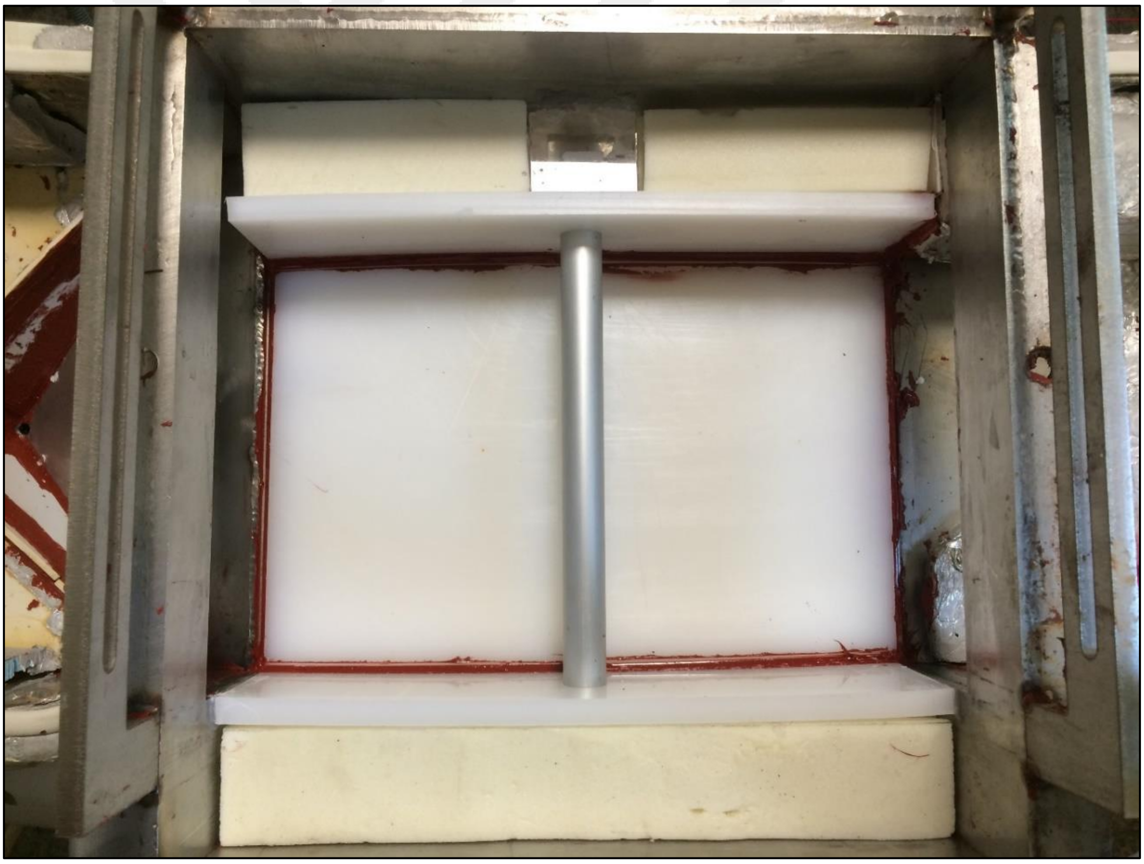

Figure 5.1. Cylindrical condenser placement inside the test section

Figure 5.2. Complete test section for the cylindrical condenser

The top part of the test section was covered by transparent Plexiglas plates to observe condensation process. During cylindrical condenser experiments, two Plexiglas plates (one in eight millimeters and the other three millimeters in thickness) were used on top of each other with air between them in order to create insulation layer as shown in Figure 5.2.

5.2. PLATE CONDENSER

The flat plate condenser consists of two parts. The top part is made of aluminum with six mm in thickness. The bottom part is made of polyamide which is resistant to corrosion and high temperature and is easy to machine. Cooling water flows between two parts. The dimension of the plate condenser is 25×20 cm.

Figure 5.3. Top view of the plate condenser made of aluminum

Total 16 stainless steel screws with countersink heads were used to seal the top part and the cast polyamide part. Countersink heads shown in Figure 5.3 were used in order not to interfere the flow of air-steam mixture as much as possible. Additionally screw holes were drilled carefully not to interfere with water flow inside the condenser as shown in Figure 5.3.

Figure 5.4. Top view of cast polyamide part

The condensation section of the cast polyamide plate, 20 mm in thickness, was milled, one mm in depth, 200 mm in length and 190 mm in width, such that cooling water flows through one mm gap between the aluminum plate and the polyamide plate. Additionally the polyamide plate was milled to have two pools at the inlet and exit. Each pool is 15 mm in depth, 15 mm in width and 190 mm in length as shown in Figure 5.4. The pools are intended to support uniform water flow in 190 mm width by creating pressure head between two pools. Four T-type thermocouples were inserted at the outlet to obtain water temperatures. The average value of four measurements by the thermocouple renders the outlet temperature of the cooling water. Thermocouples were sealed in the holes with heat and water-resistant silicone and water-resistant glue.

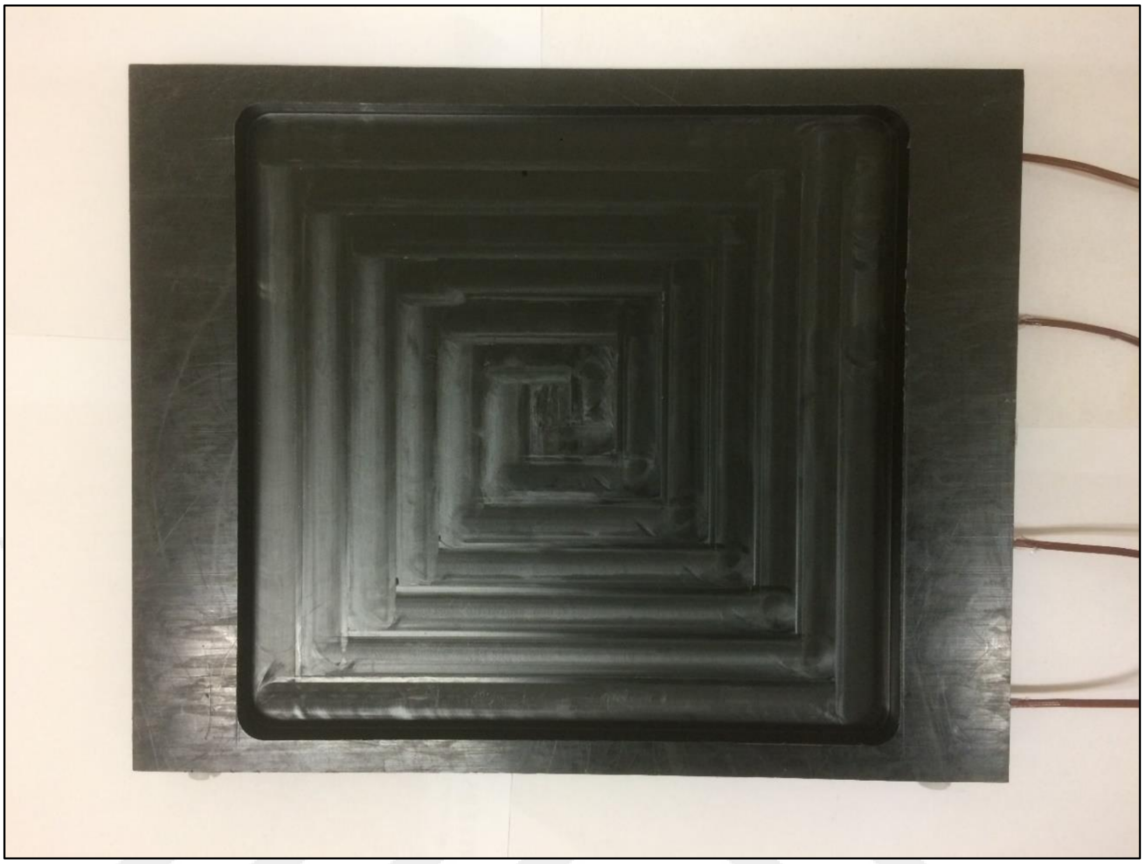

Figure 5.5. Bottom view of the cast polyamide base part

The bottom of the cast polyamide part was milled by 180×180×15 mm in order to reduce thermal mass and fill insulation material in the space as seen in Figure 5.5. The insulation placed into the bottom part of the condenser is estimated to reduce heat loss by an order of two watts (see Figure 5.6).

Figure 5.6. Thermocouple placement under the bottom part

Two thermocouples were placed under the bottom polyamide part in order to measure temperature difference between bottom part and insulation. In order to obtain more uniform water flow inside, as shown in Figure 5.6, four holes each at the inlet and outlet of the cast polyamide were drilled for eight pneumatic heads, 3/8”-10mm in side.

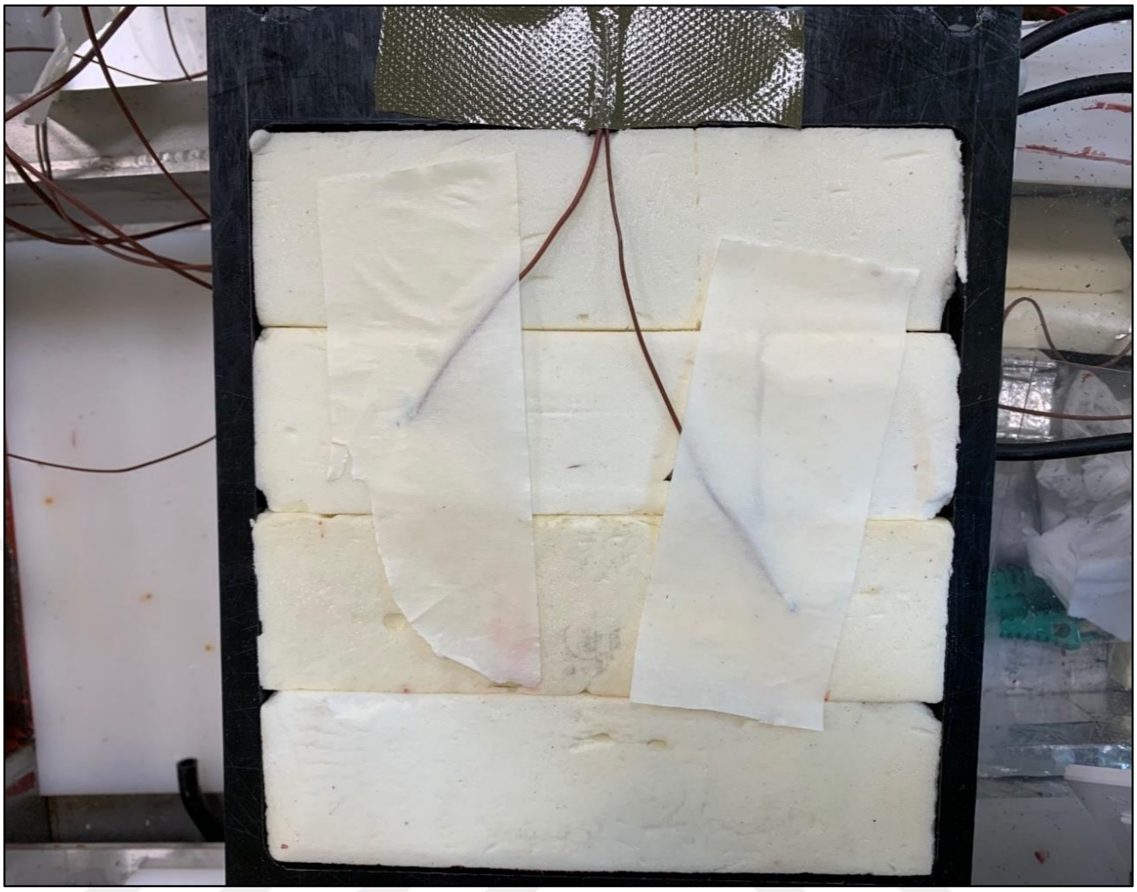

Figure 5.7. Insulation of the bottom and thermocouple placement

Two thermocouples were placed on top of the insulation as shown in Figure 5.7. Resistance heater with 25 Ω resistance was placed under the insulation to heat bottom part according to temperature difference between two sides of the insulation.

Figure 5.8. Resistance heater placed under the polyamide base.

Temperature data from inside and outside of insulation was observed from the data acquisition software and adequate power was supplied to the resistance heater in order to reduce heat loss from bottom part as much as possible by keeping temperatures as close as possible.

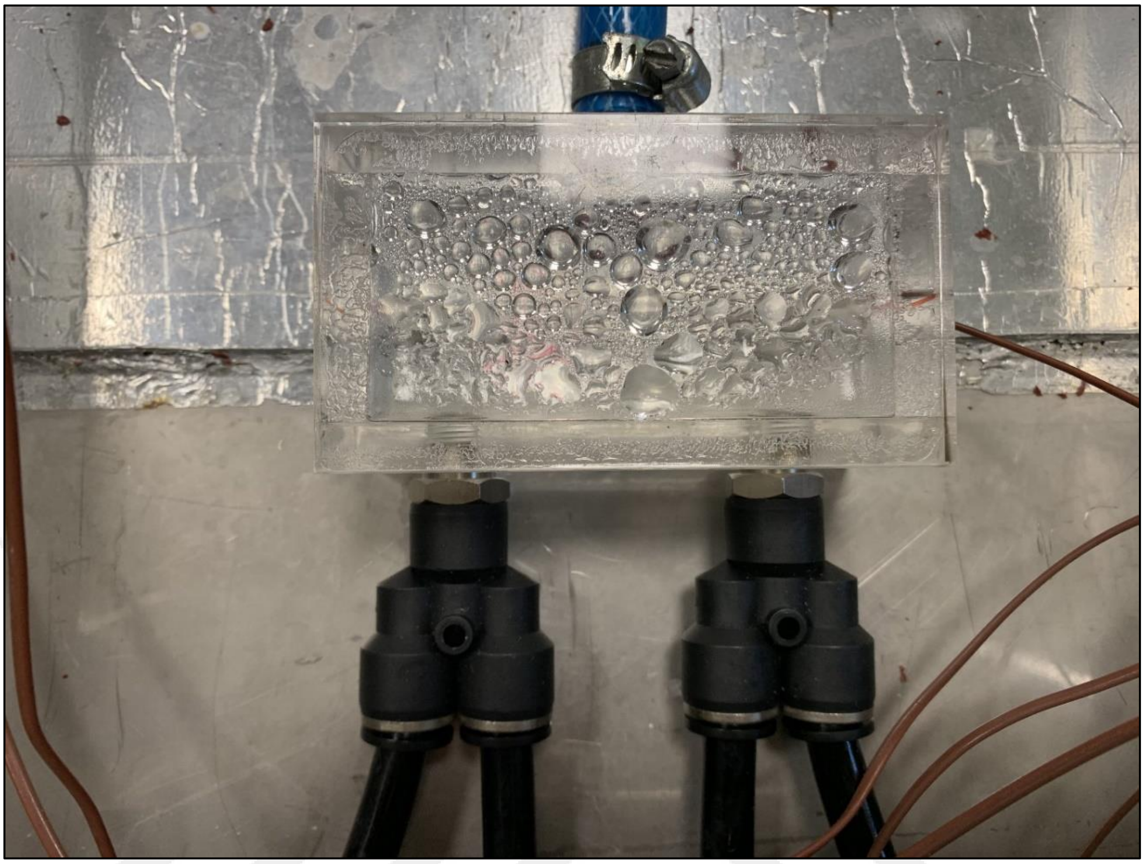

Figure 5.9. Separators and accumulator boxes at the inlet and outlet

Four pneumatic hoses connected to push-in pneumatic heads were then connected to two 3/8”-10 mm Y pushes which were in turn connected to a water mixing chamber as shown in Figure 5.9. The purpose of the mixing chamber was to measure the bulk temperature of water at the outlet. Figure 5.9 also shows a thermocouple that was carefully located at the center of a three millimeter Plexiglas wall in the middle of the mixing chamber in order to obtain better average temperature.

Two mixing chambers, one at the inlet and the other at the outlet of the test section, were made of Plexiglas pieces, eight millimeter in thickness, which were glued by chloroform. The mixing chamber at the inlet was to separate cooling water from a single inlet hose to four channels, intending to provide more uniform water flow inside the plate condenser. Inlet water temperature was measured at the inlet mixing chamber, and outlet temperature was obtained by averaging measurements from four thermocouples at the outlet side of the cast polyamide base.

Figure 5.10. Thermocouple testing for water leak

It is known that water can leak between the brown outer jacket and thermocouple wires, resulting that water flows along the thermocouple wire to DAQ carts, subsequently causing the failure of DAQ. Therefore, the space between the outer jacket and the insulating plastics of two thermocouple wires was glued with water-resistant glue. Then it was tested for two days as shown in Figure 5.10 to see if there is water leak along thermocouple cables.

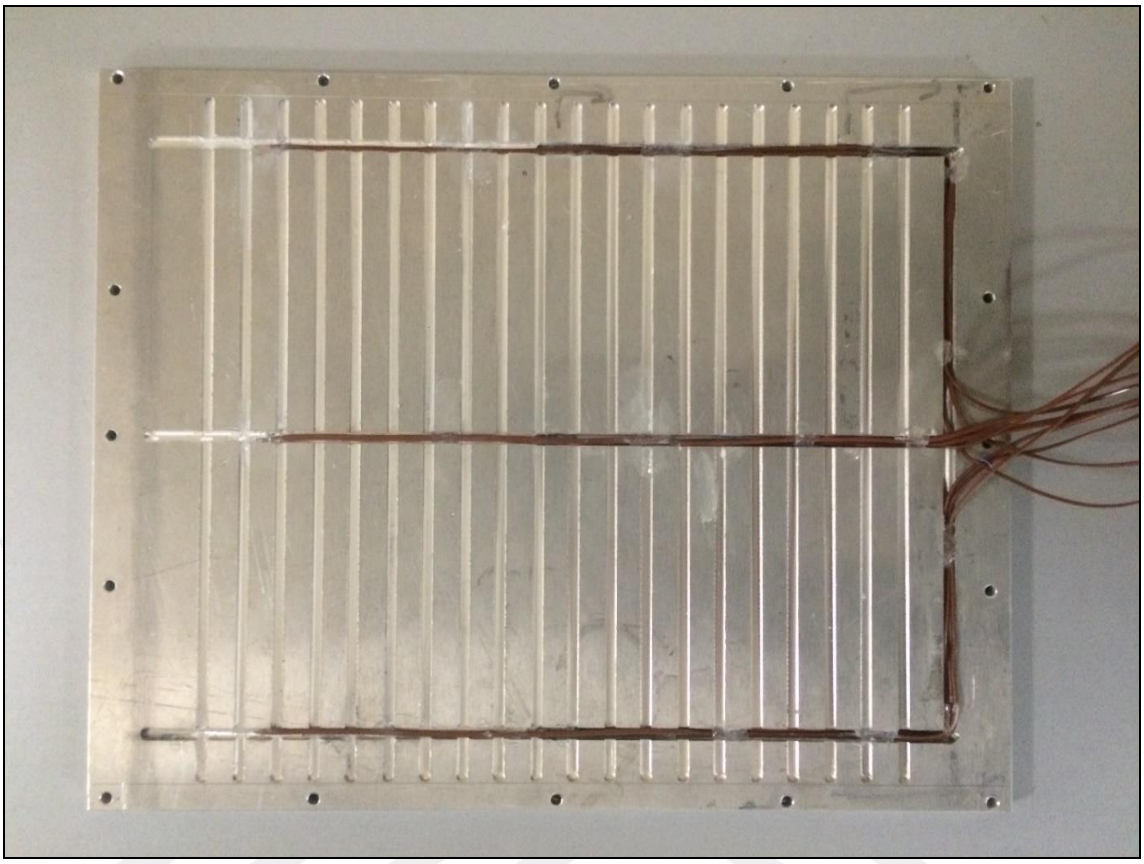

Figure 5.11. Bottom view of the aluminum condenser part

Three horizontal channels, as shown in Figure 5.11, were milled to place thermocouples which measure the surface temperatures of the aluminum condenser. Each channel accommodated three thermocouples. Therefore, total nine thermocouples provided the temperature distribution of the aluminum plate. In order to fit all three thermocouples in one channel, milling depth was one millimeter for the first thermocouple wire, two millimeters for the second thermocouple wire and three millimeter for the third thermocouple wire. Thermocouple tips were soldered flat in order to be in complete contact with the aluminum surface, thus providing more accurate temperature measurements. Then the flattened thermocouple tips were carefully glued to the aluminum channel.

Additionally 20 vertical channels with each 10 mm interval were milled across the water flow direction in order to restart boundary layer development which would increase heat transfer rate between water and the aluminum surface.

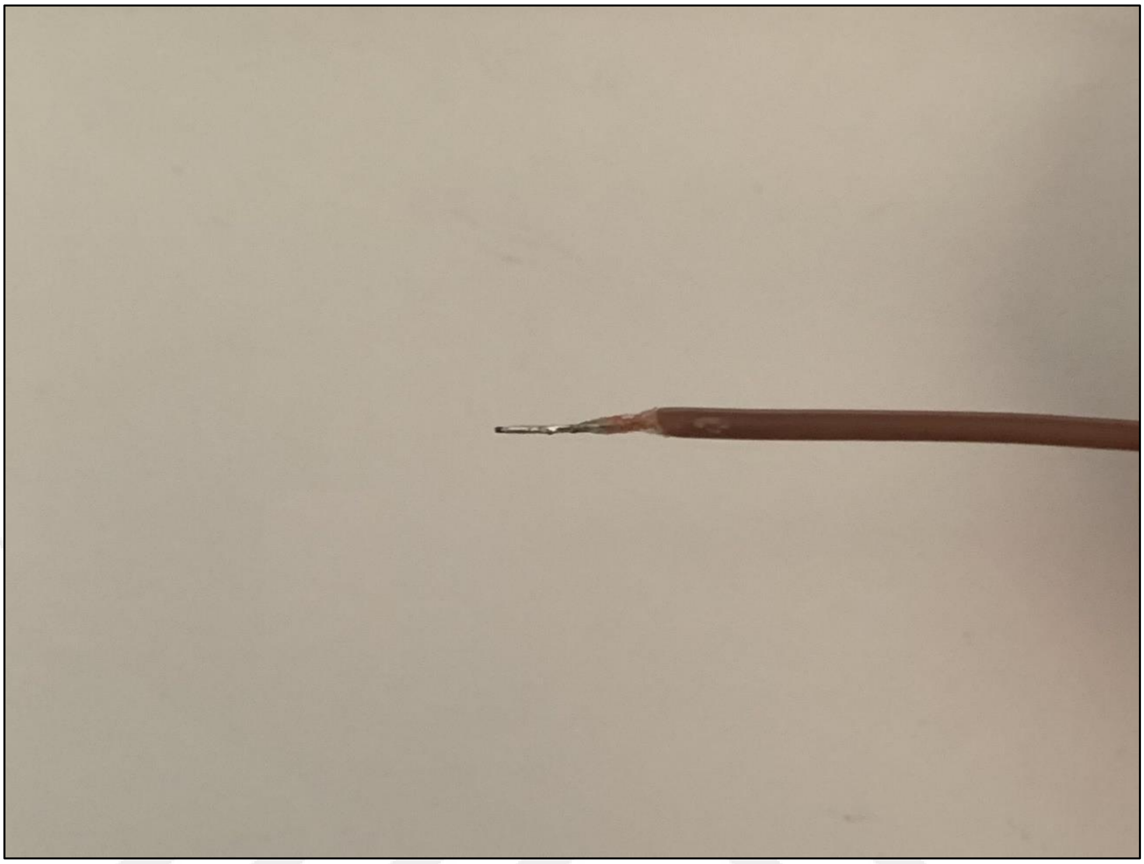

Figure 5.12. Thermocouple soldering and isolation example

Figure 5.12 shows how a thermocouple tip was flat soldered and how water leak was prevented by applying glue on the tip of the brown jacket of the thermocouple.

Figure 5.13 shows Plastic bolts that were placed at both inlet and outlet pools to empty water out of the condenser if necessary.

Figure 5.13. Side view of the cast polyamide base

Figure 5.14. Insulation placement on the stainless steel part of the test section

Before the condenser was installed in the test section, insulators were placed at the bottom of the test section as shown in Figure 5.14. Five small Plexiglas parts were placed under the insulation to avoid sinking of the test section due to high temperatures and weight.

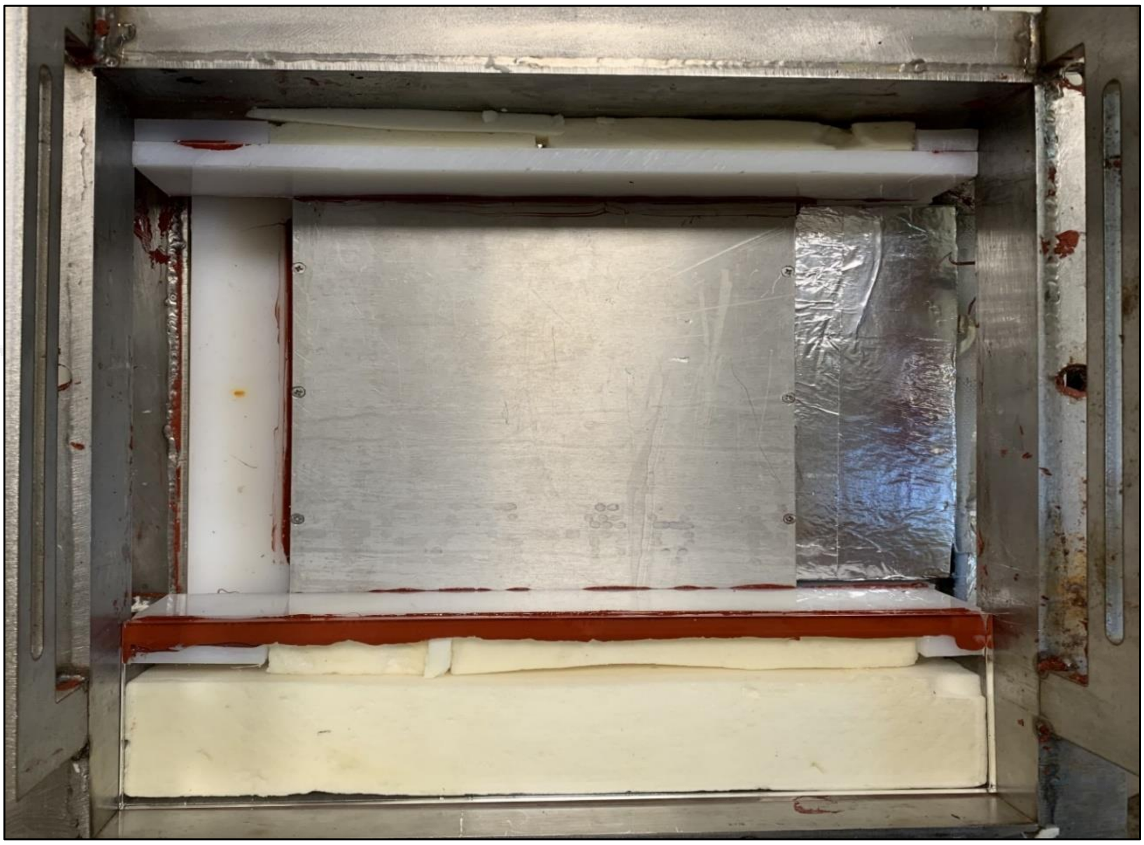

Figure 5.15. Plate condenser placement inside the test section

After placing the inlet water mixing chamber inside the stainless steel case and connecting the inlet fittings, inlet and outlet sections were insulated completely and sealed shut with heat-resistant silicone as seen in Figure 5.15. Test section dimensions are 20 cm in width and 19 cm in length. Plastic part under the plate condenser was sealed from air-vapor mixture inlet and outlet side with heat and water resistant silicone in order to avoid water leaks to the condensate. Two thermocouples were placed at the mixture inlet and outlet in order to employ LMTD method during overall heat transfer coefficient calculations. Three dimensional model of the test section is shown in Figure 5.16.

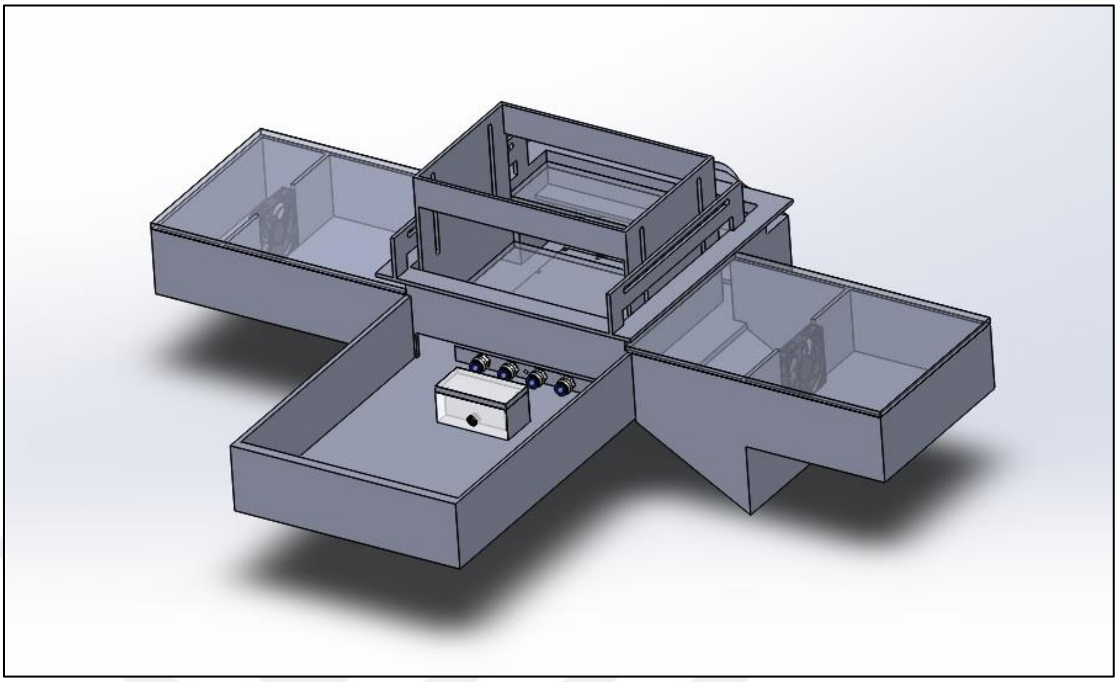

Figure 5.16. 3D model of the flat plate condenser setup

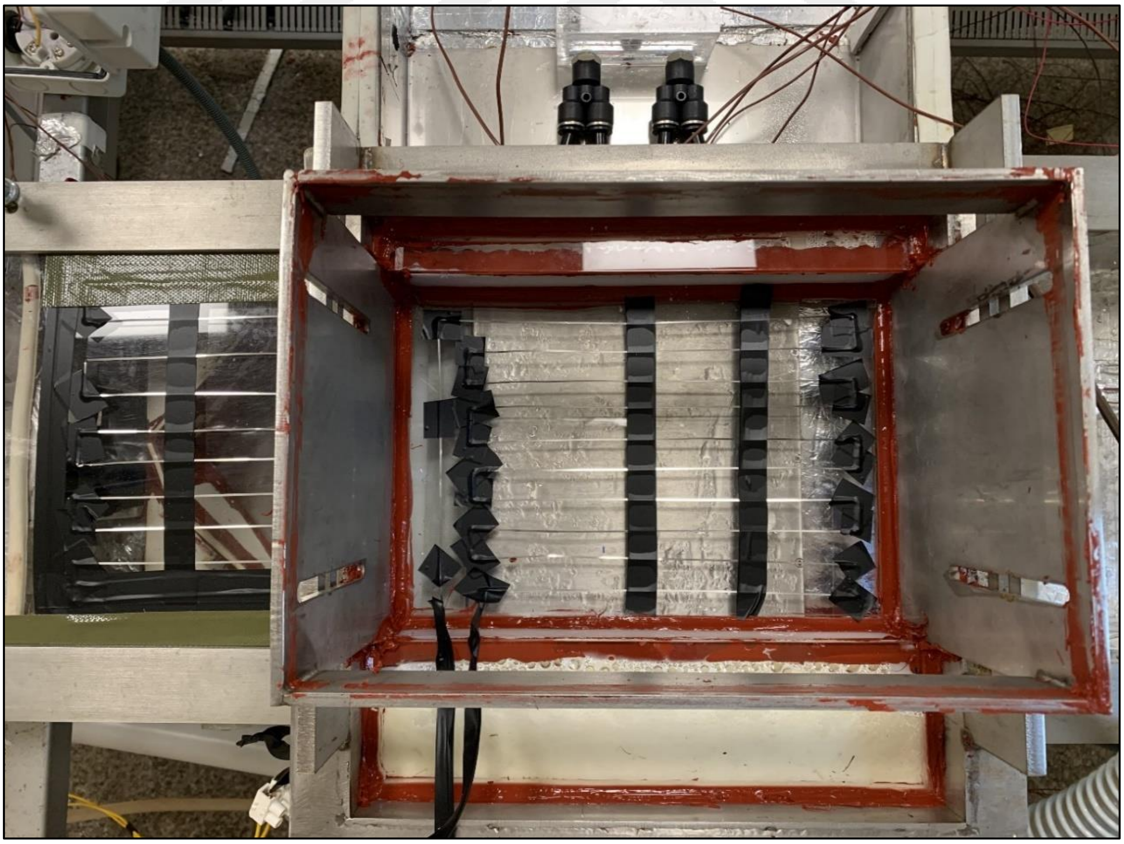

Figure 5.17. Complete view of the plate condenser test section

Air flow channel height can be adjusted by moving the top part as shown in Figure 5.17. In the present study, channel height was set to 10 mm. Resistance heaters were placed on the top of eight millimeter Plexiglas plate to reduce condensation at the bottom of the Plexiglas plate. The power of the heaters were adjusted with a dimmer and were monitored not to provide undesired heat to the test section. The power usage of 30W was found to be adequate.

6. EXPERIMENTAL PROCEDURE

Experimental procedure was exactly the same for both cylindrical and flat plate condensers. Steps followed in these experiments are listed below;

- Water temperature controller, thermostat is opened to heat water up to experiment temperature.
- CTF controller computer was turned on.
- Power supplies connected to resistance heaters and the water pump were turned on and set to specific voltage value to avoid heat addition to the test section.
- CTF temperature was set to experiment temperature without humidity in order to warm up the CTF more rapidly. It takes around two hours to warm up from a cold start.
- The water level of the dry-wet bulb humidity-measuring device was checked every 30 minutes.
- The water level of the boiler was checked every 30 minutes during experiments to prevent overheating of the resistance heater inside the boiler in case of insufficient water. Added water if it’s below red mark.
- After the warm up period, humidity control was turned on to reach the target value of relative humidity. It took around 30 minutes to reach steady state after the desired humidity level was reached.
- Inlet and outlet temperature difference was kept at between 5-8°C by using the valve at the outlet.
- Data acquisition software and digital scale were turned on.
- Data acquisition device and digital scale were started to record data every second.
- A beaker and a stopwatch were used to calculate cooling water flow rate.
- After data collection, humidity control was turned off in order to dry out condensate built up around test section.

7. EXPERIMENTAL RESULTS AND DISCUSSION

At each setting of a test, data were taken for 30 minutes with no break, but the whole data were divided into six subsets with the interval of five minutes each. Thus the variation of measurements over the time period was examined. Therefore, at each run, six experimental results are presented in the following.

Two geometric types of condensers were considered. Experiments were done with a cylindrical condenser and then a flat plate condenser.

Error bars with 95 percent confidence interval were drawn on each data point to indicate the uncertainty of the data.

7.1. FLAT PLATE CONDENSER RESULTS

7.1.1. Relative Humidity vs. Condensation Efficiency

Figure 7.1 shows the condensation efficiency as a function of relative humidity at the mixture flow rate of 12 l/s. In general, it appears that the higher the relative humidity, the higher the efficiency. When data are closely examined, it was found that for the relative humidity of 60 and 80 percent the condensation efficiency increased with increasing cooling water temperature. But it could not be said for the case of 70 percent relative humidity at which the cooling water temperature of 30°C yields the highest efficiency. The highest condensation efficiency was obtained to be 86 percent at the cooling water temperature of 40°C and the relative humidity of 80 percent. A few experiments were conducted to check repeatability for the cooling water temperature of 30°C and 40°C and the relative humidity of 70 percent. Those data were found to be within the range of error bars.

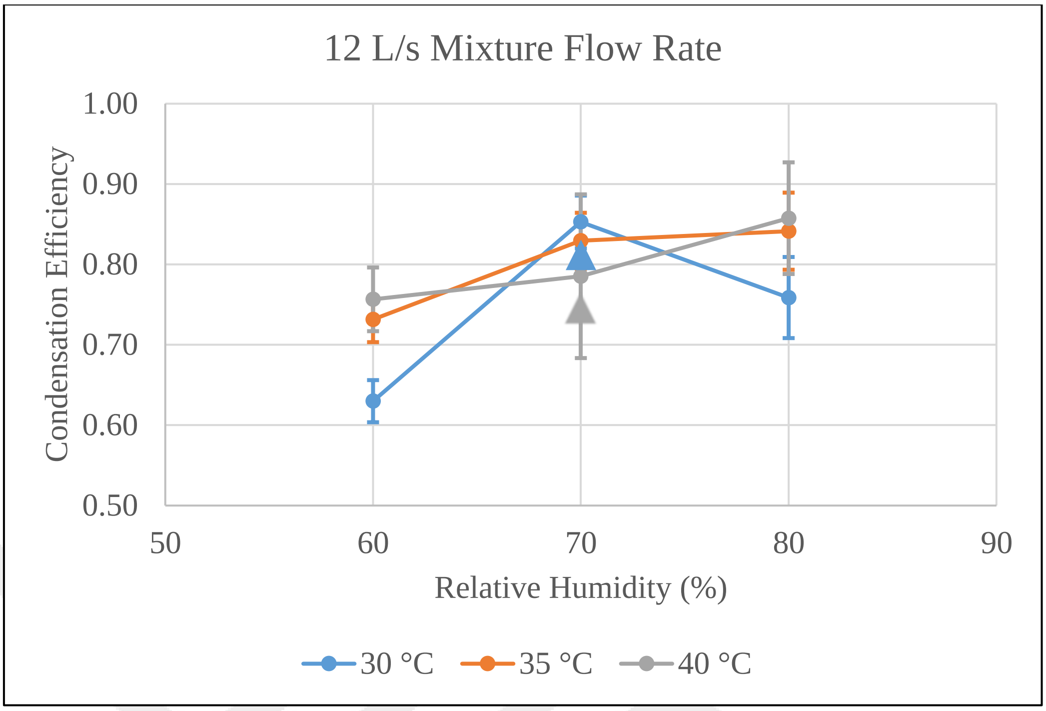

Figure 7.1. Relative humidity vs. condensation efficiency at 12 l/s mixture flow rate; ∆, the test data to check repeatability

16 l/s mixture flow rate experiments can be seen in Figure 7.2, condensation efficiency was higher for 40°C cooling water temperature than 30°C and 35°C for 70 percent and 80 percent humidity but this trend was not visible for 60 percent. Experiments done with cooling water temperature of 35°C at 16 l/s mixture flow rate shows that condensation efficiency increases as relative humidity increases. Highest condensation efficiency was obtained at 40°C and 80 percent humidity as 87.5 percent.

As in 12 l/s and 16 l/s results, condensation efficiency was highest at 80 percent and 40°C experiments in 20 l/s mixture flow rate setting in Figure 7.3. Highest condensation efficiency was 90 percent during 40°C, 80 percent experiments. Lowest condensation value was 52 percent due to vaporization of condensate.

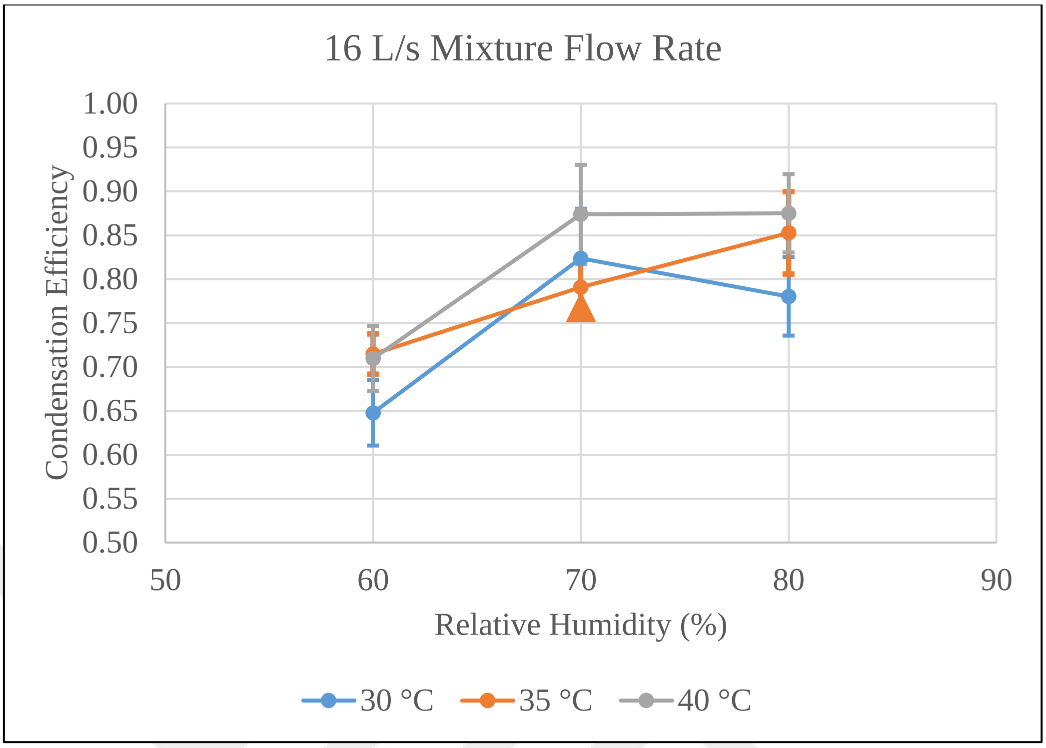

Figure 7.2. Relative humidity vs. condensation efficiency at 16 l/s mixture flow rate; ∆, the test data to check repeatability

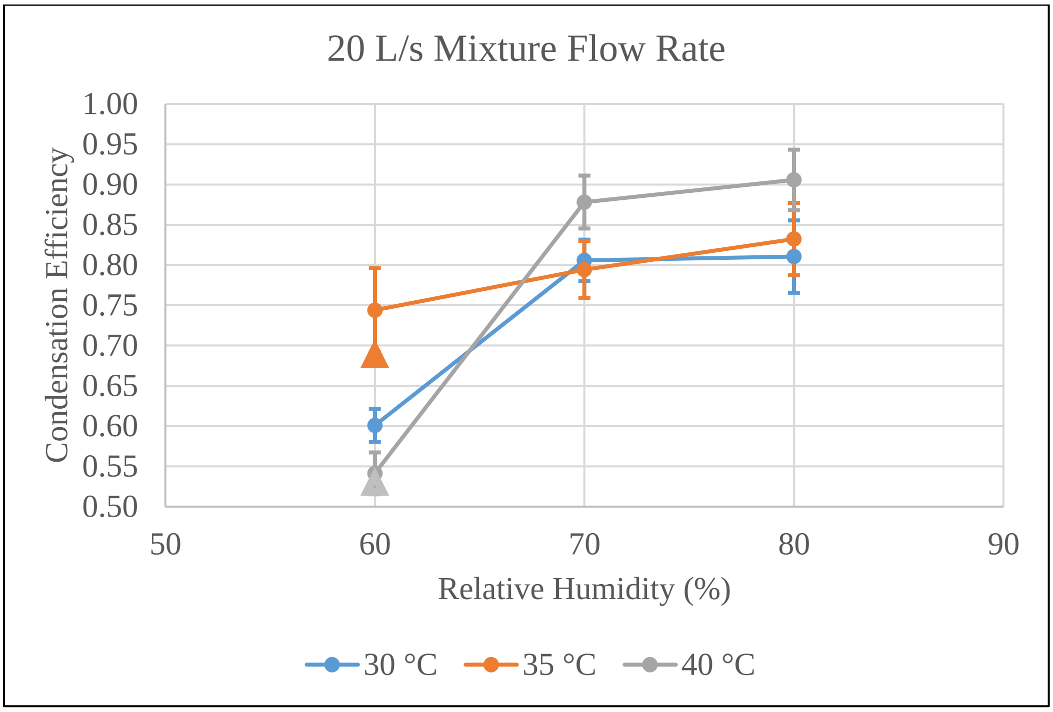

Figure 7.3. Relative humidity vs. condensation efficiency at 20 l/s mixture flow rate; ∆, the test data to check repeatability

7.1.2. Mixture Flow Rate vs. Condensation Efficiency

60 percent relative humidity experiments are shown in Figure 7.4, condensation efficiency drops to lowest value of 52 percent as shown. This occurs due to vaporization of condensate due to very high mixture flow rate and high surface temperature of the aluminum condenser. Additional experiments were done at 18 l/s mixture flow rate as shown with black and red points. Highest condensation efficiency was obtained at 40°C and 12 l/s mixture flow rate as 76 percent.

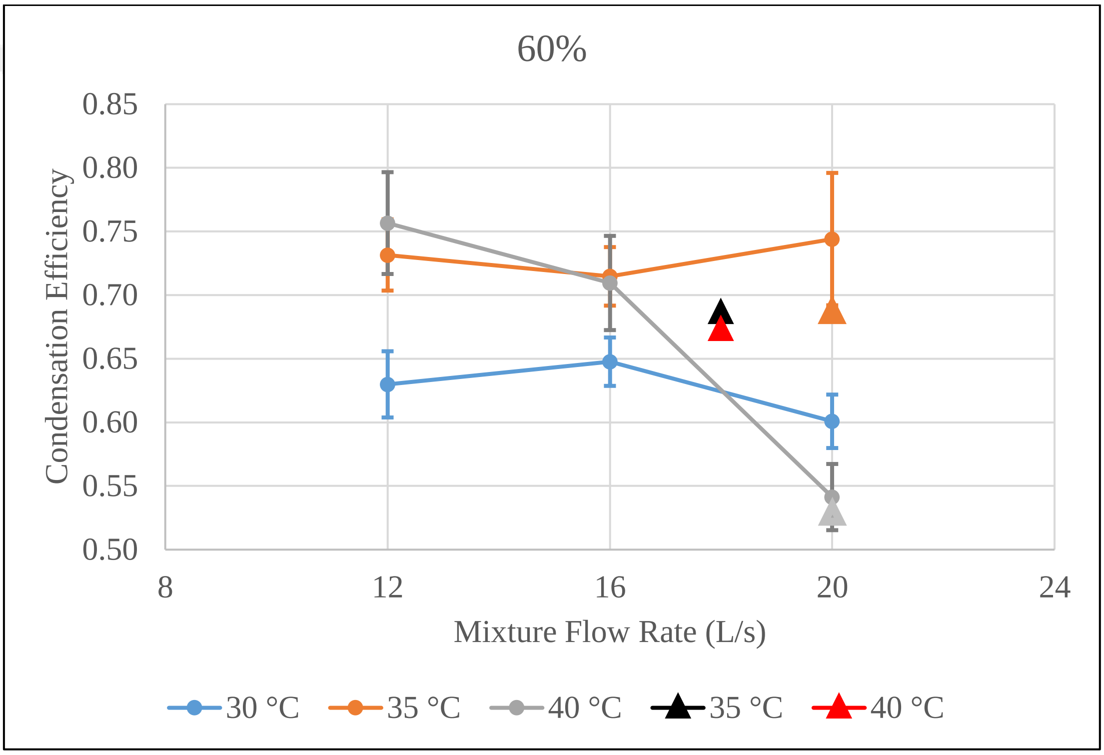

Figure 7.4. Mixture flow rate vs. condensation efficiency at 60%; ∆, the test data to check repeatability

Highest condensation efficiency was obtained during 20 l/s and 40°C cooling water temperature as 88 percent as shown in Figure 7.5. There is no clear general trend for condensation efficiency with respect to mixture flow rate. For cooling water temperature of 30°C, condensation efficiency decreases from 85 percent to 82 percent and finally 80 percent as mixture flow rate increases from 12 l/s to 16 l/s and 20 l/s respectively. During 35°C cooling water temperature experiments, condensation efficiency decreaeses as mixture flow rate is increased from 12 l/s to 16 l/s then slightly increases as mixture flow rate increases to 20 l/s. For cooling water temperature of 40°C, condensation efficiency trend is opposite of 30°C and 35°C as it increases with increasing mixture flow rate but there is very little change when mixture flow rate is increased to 20 l/s.

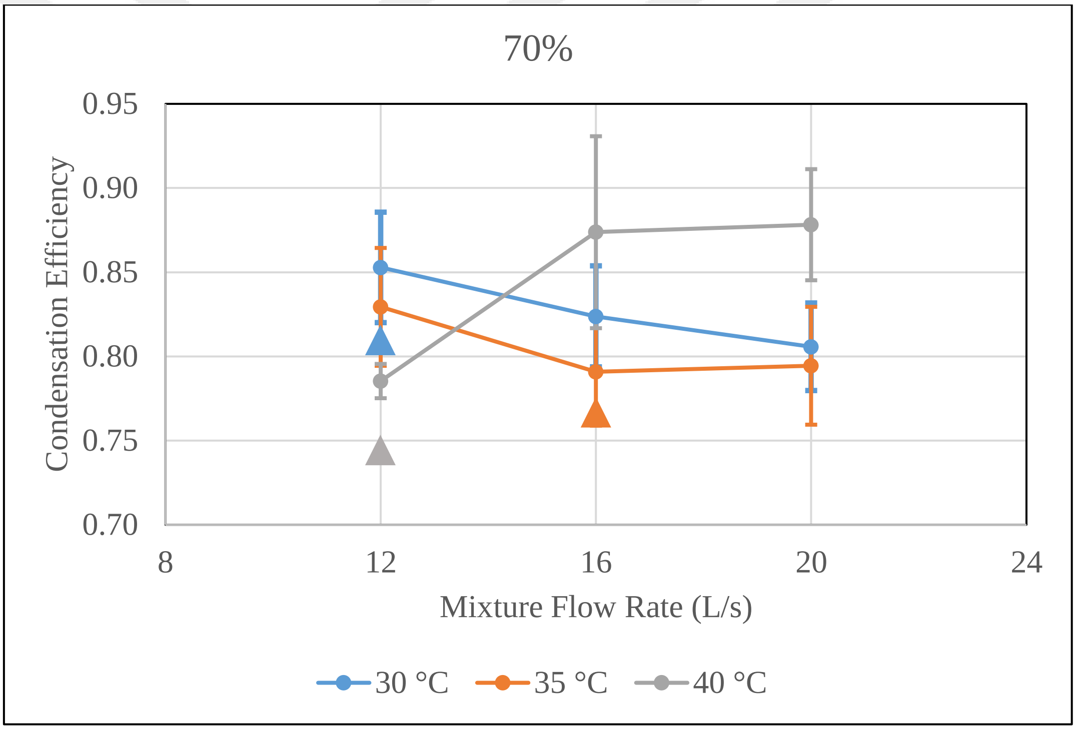

Figure 7.5. Mixture flow rate vs. condensation efficiency at 70%; △, the test data to check repeatability

During 80 percent experiments which can be seen in Figure 7.6, 40°C cooling water temperature yielded higher condensation efficiency results than 35°C and 30°C. For 30°C and 40°C cooling water temperatures, condensation efficiency increased with respect to mixture flow rate while it was not observed for 35°C.

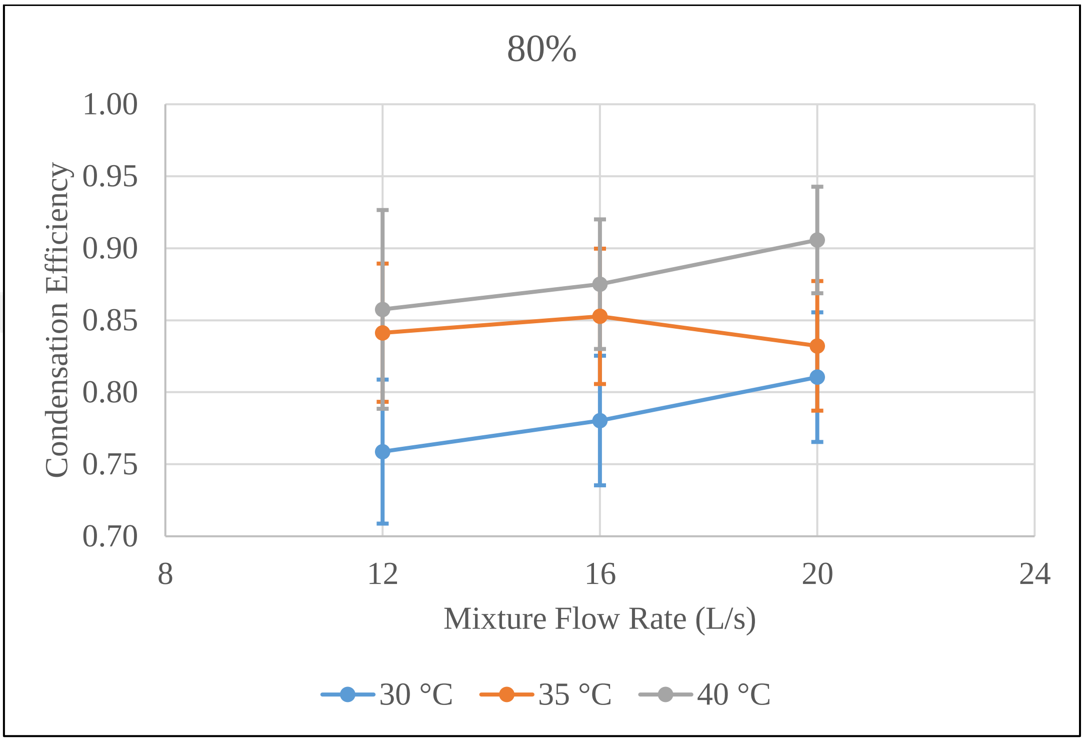

Figure 7.6. Mixture flow rate vs. condensation efficiency at 80%; △, the test data to check repeatability

7.1.3. Cooling Water Temperature vs. Condensation Efficiency

As explained above, lowest condensation efficiency was obtained during 40°C cooling water temperature 20 l/s mixture flow rate as 52 percent. Highest condensation efficiency was obtained at mixture flow rate of 12 l/s and cooling water temperature of 40°C. The efficiency results decrease with increasing mixture flow rate at 40°C and 60% humidity but this trend was not visible for cooling water temperatures of 30°C and 35°C as shown in Figure 7.7.

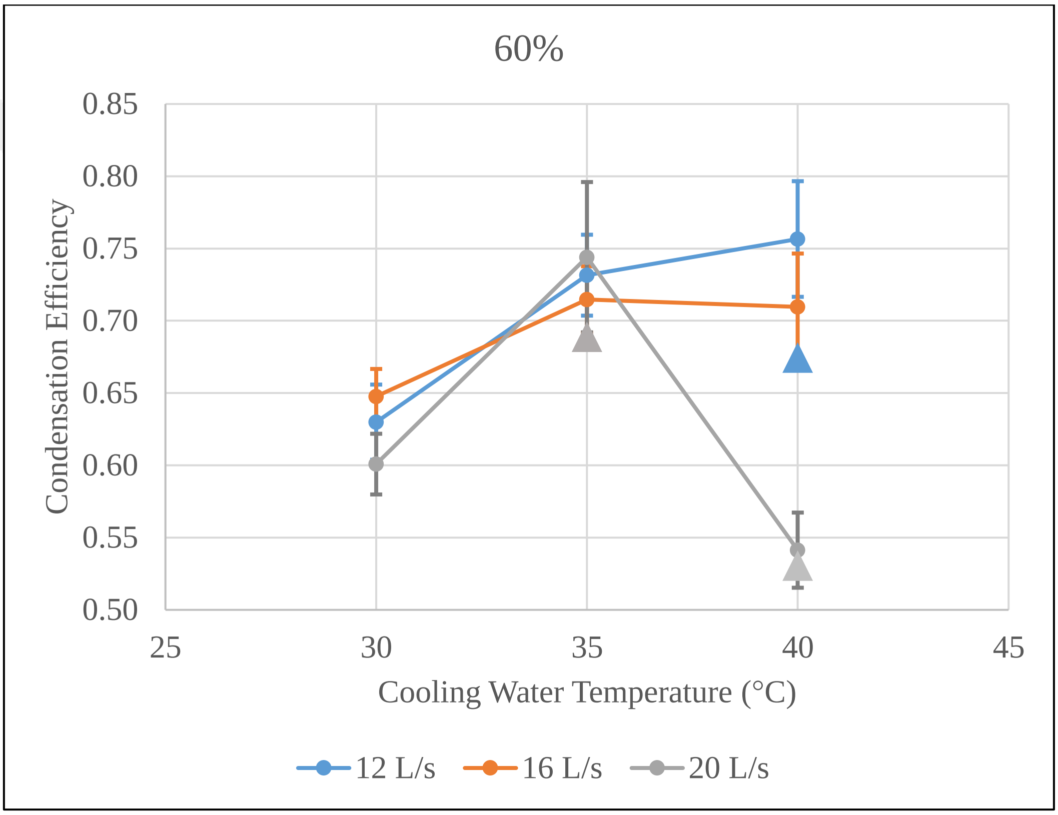

Figure 7.7. Cooling water temperature vs. condensation efficiency at 60%; △, the test data to check repeatability

During 70 percent relative humidity experiments which can be seen in Figure 7.8, highest condensation efficiency was obtained at 40°C cooling water temperature and 20 l/s mixture flow rate. Mixture flow rate of 16 l/s and 20 l/s yielded similar results especially at cooling water temperatures of 35°C and 40°C. Lowest condensation efficiency was obtained during 40°C cooling water temperature and 12 l/s mixture flow rate as 78.5 percent.

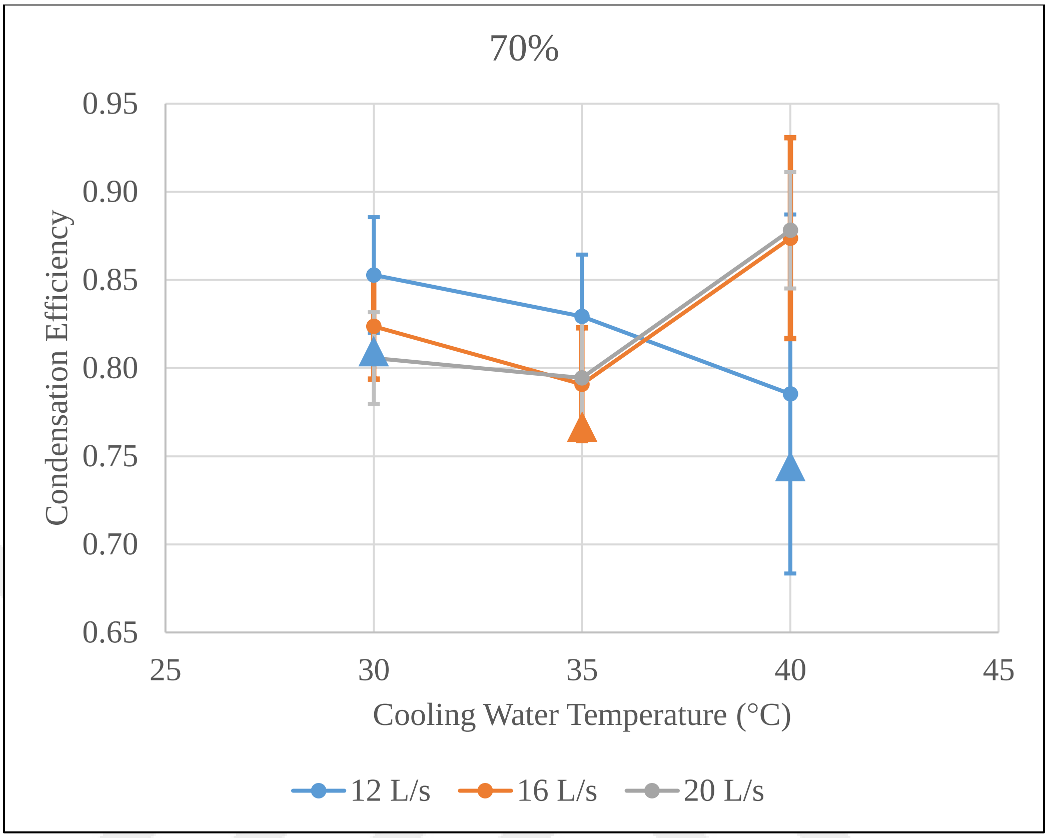

Figure 7.8. Cooling water temperature vs. condensation efficiency at 70%; ∆, the test data to check repeatability

During 80 percent humidity experiments, increasing cooling water temperature increased condensation efficiency as seen in Figure 7.9. 20 l/s mixture flow rate had higher condensation efficiency results during 30°C and 40°C experiments than 12 l/s and 16 l/s but lowest during 35°C cooling water temperature. During 70 percent and 80 percent relative humidity experiments, highest condensation efficiency was obtained with 20 l/s mixture flow rate. At 80 percent humidity, the trend is clear that the efficiency increases with the increasing the cooling water temperature at inlet.

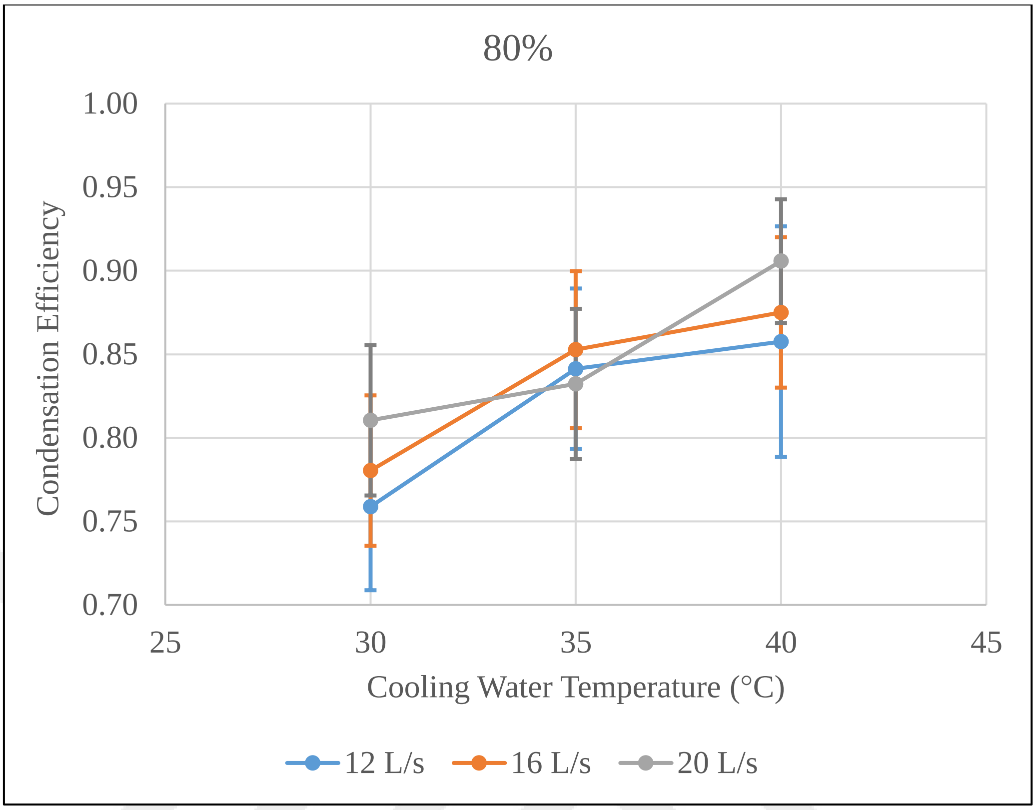

Figure 7.9. Cooling water temperature vs. condensation efficiency at 80%; △, the test data to check repeatability

7.1.4. Overall Heat Transfer Coefficient Results

For 30°C cooling water temperature, overall heat transfer coefficient increases with increasing mixture flow rate and relative humidity which can be seen in Figure 7.10. Increase in overall heat transfer coefficient is higher for higher humidity values. For example, in 60 percent setting overall heat transfer coefficient raises from 259 W/m^2 K to 303 W/m^2 K while in 80 percent setting, U value increases from 586 W/m^2 K to 724 W/m^2 K.

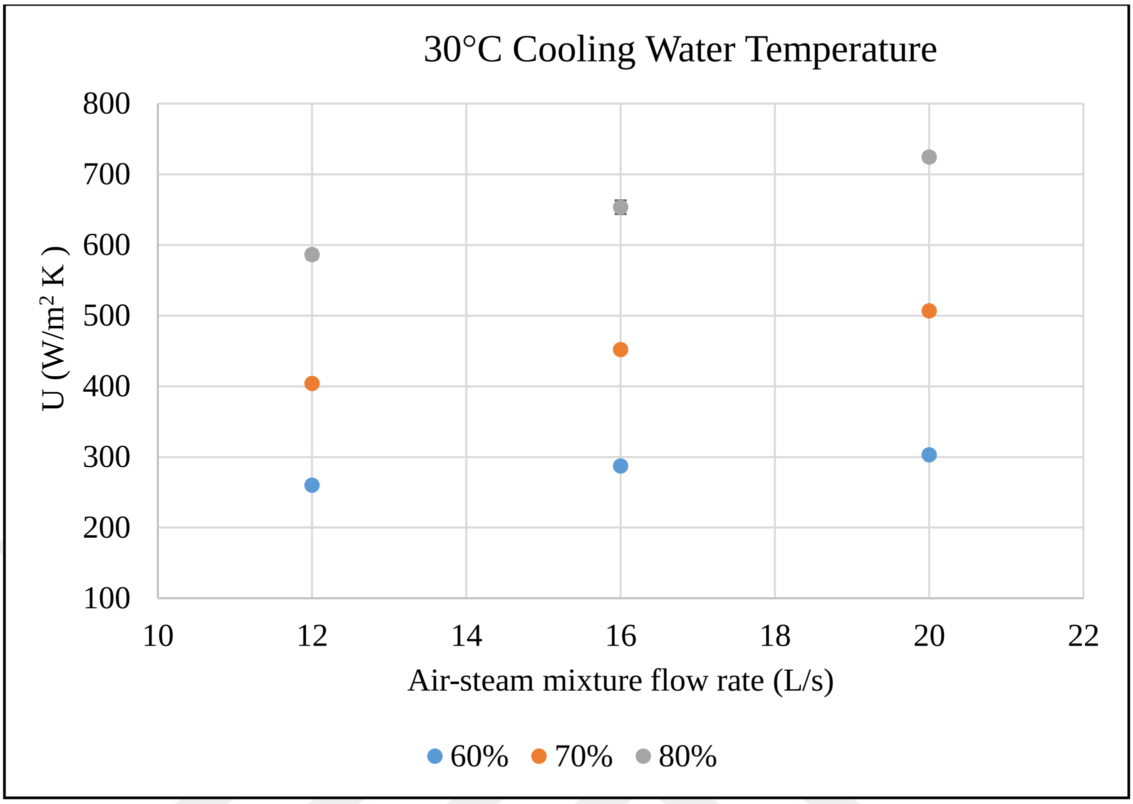

Figure 7.10. Overall heat transfer coefficient results at 30°C cooling water temperature.

Results show that for 35°C cooling water temperature in Figure 7.11, overall heat transfer coefficient increases with increasing relative humidity and mixture flow rate. For the relative humidity of 60 percent and 70 percent, the values of the overall heat transfer coefficient at 35°C cooling water temperature are similar to those at 30°C cooling water temperature. In Figure 7.12, it can be seen that overall heat transfer coefficients were lower for 40°C than 30°C and 35°C.

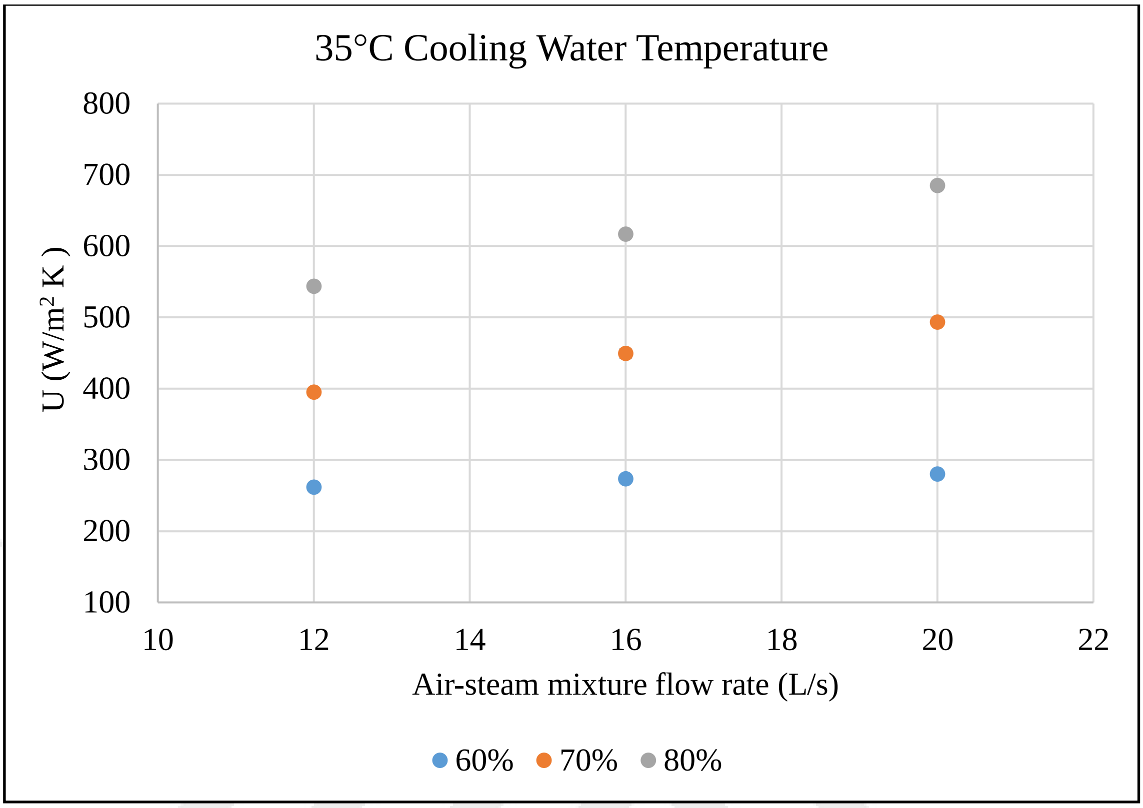

Figure 7.11. Overall heat transfer coefficient results at 35°C cooling water temperature.

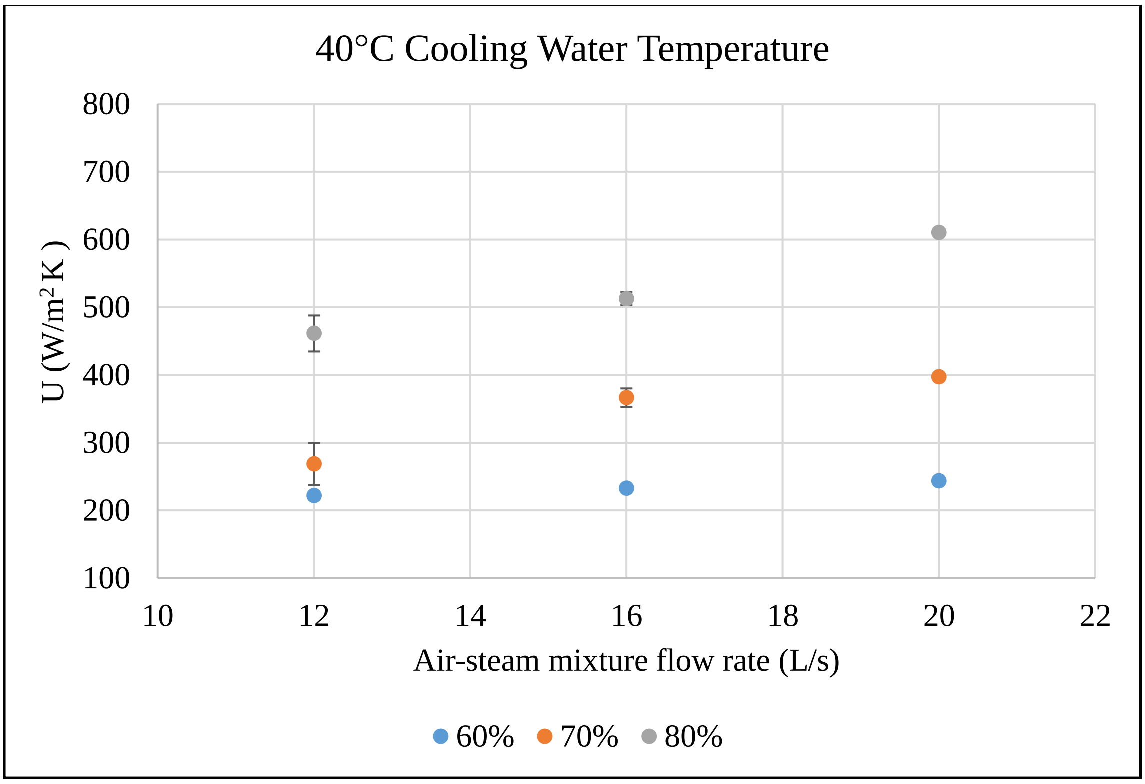

Figure 7.12. Overall heat transfer coefficient results at 40°C cooling water temperature.

Overall heat transfer coefficient decreases as cooling water temperature increases in all cases, can be seen in Figures 7.13, 7.14, 7.15. Figure 7.13 shows relation between cooling water temperature and overall heat transfer coefficient at mixture flow rate of 12 l/s. Highest U value was obtained at cooling water temperature of 30 °C and 60 percent humidity as 586 W/m^2K. U values decreases with increasing cooling water temperature and relative humdity for most experiments except for the 60 percent and 35°C. Lowest U value was obtained at cooling water temperature of 40°C and 60 percent as 221 W/m^2K. Drop in overall heat transfer coefficient is more evident while increasing cooling water temperature from 35°C to 40°C than 30°C to 35°C.

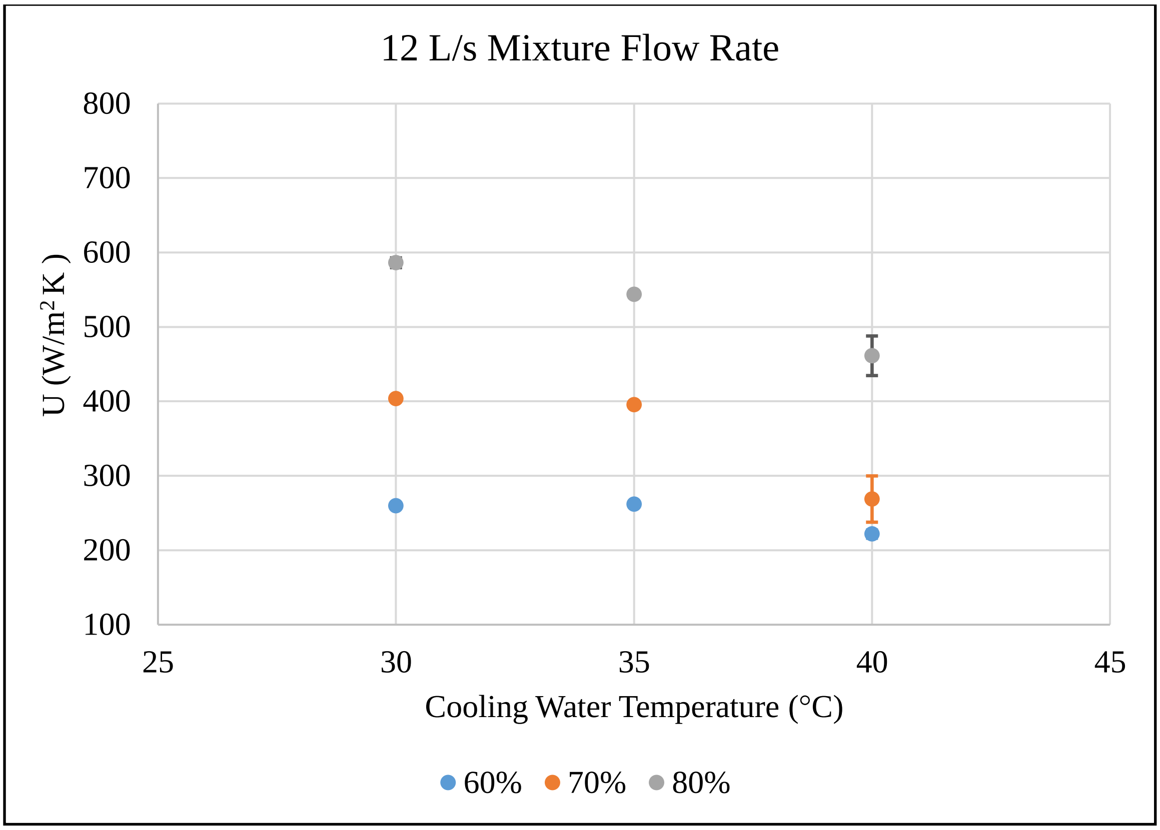

Figure 7.13. Overall heat transfer coefficient vs. mixture flow rate at 12 l/s.

In Figure 7.14, relation between cooling water temperature and overall heat transfer coefficient at mixture flow rate of 16 l/s can be seen. Highest U value was obtained at cooling water temperature of 30 °C and 60 percent humidity as 653 W/m^2K which is higher than the 12 l/s experiments. U values decreases with increasing cooling water temperature and relative humdity for all experiments. Lowest U value was obtained at cooling water temperature of 40°C and 60 percent as 232 W/m^2K. Drop in overall heat transfer coefficient is more evident while increasing cooling water temperature from 35°C to 40°C than 30°C to 35°C that was also visible in mixture flow rate of 12 l/s.

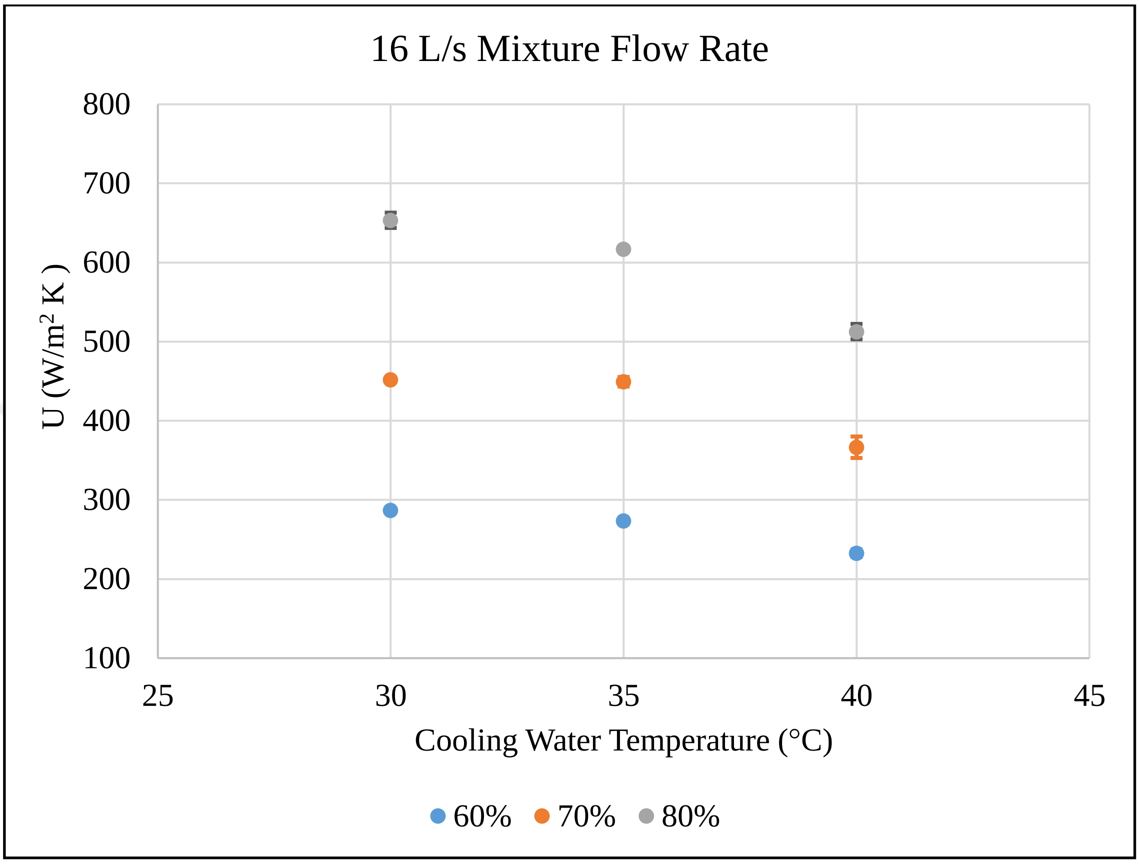

Figure 7.14. Overall heat transfer coefficient vs. mixture flow rate at 16 l/s.

In Figure 7.15, relation between cooling water temperature and overall heat transfer coefficient at mixture flow rate of 20 l/s can be seen. Highest U value was obtained at cooling water temperature of 30 °C and 60 percent humidity as 724 W/m^{2}K which is the highest U value in all experiments. As in other mixture flow rates, U values decreases with increasing cooling water temperature and relative humdity. Lowest U value was obtained at cooling water temperature of 40°C and 60 percent as 243 W/m^{2}K.

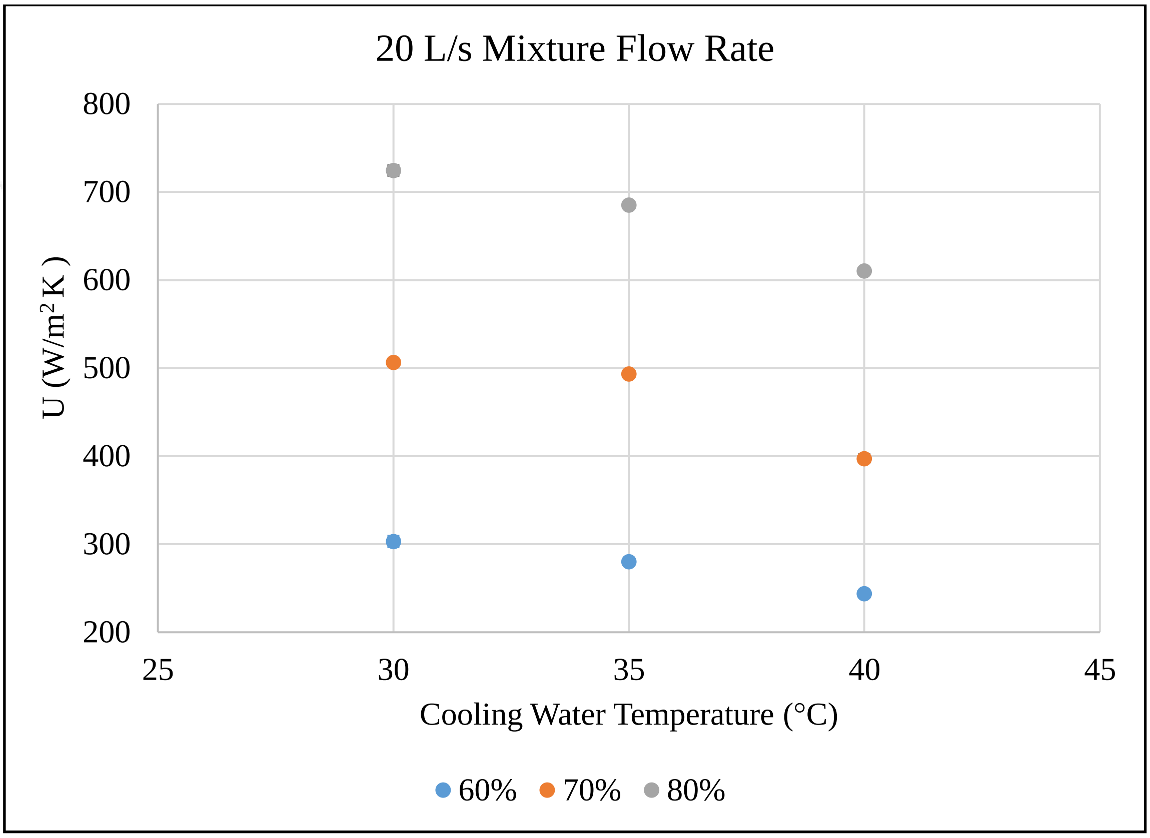

Figure 7.15. Overall heat transfer coefficient vs. mixture flow rate at 20 l/s.

7.2. CYLINDRICAL CONDENSER RESULTS

Cylindrical condenser experiments were done at two different mixture temperatures which are 60°C and 70°C. For both temperature setup, relative humidity values of 70 percent, 80 percent and 90 percent were investigated and at each relative humidity, mixture flow rates of 18 l/s and 24 l/s were experimented.

7.2.1. Results of Humid Air Temperature at 60°C

During humid air temperature of 60°C experiments, mixture flow rate and relative humidity values were set to 18 l/s and 70 percent respectively. After obtaining data at each relative humidity parameter, mixture flow rate was increased to 24 l/s and each humidity value was repeated. Unlike flat plate condenser setup, cooling water temperature was constant at 30°C for all experiments.

7.2.1.1. Case of 70 Percent Relative Humidity and 18 (L/s) Flow Rate

Average efficiency was found 59.3 percent for case of 70 percent relative humidity and 18 l/s mixture flow rate as seen in Table 7.1 which is higher than the case of 70 percent and 24 l/s. 30 minutes of data were collected and then divided in to three parts of 10 minutes each.

Table 7.1. 60°C, 70%, 18 l/s Results

	Exp1	**Exp2**	**Exp3**
Air flow rate (l/s)	18	18	18
Air humidity (%)	70	70	70
Water flow rate (kg/s)	2.36E-03	2.23E-03	2.28E-03
T1 (^{o}C)	30.18	30.24	29.78
T2 (^{o}C)	36.79	36.73	36.57
Condensate rate (kg/s)	1.59E-05	1.43E-05	1.66E-05
Air temperature (°C)	60	60	60
Q (kW)	0.065	0.060	0.065
dTm	26.52	26.52	26.83
U (kW/m^2 K)	0.206	0.191	0.202
Efficiency	0.59	0.57	0.62

7.2.1.2. Case of 80 Percent Relative Humidity and 18 (L/s) Flow Rate

Average efficiency was found 69 percent for 80 percent 18 l/s as seen in Table 7.2.

Table 7.2. 60°C, 80%, 18 l/s Results

	Exp4	**Exp5**	**Exp6**
Air flow rate (l/s)	18	18	18
Air humidity (%)	80	80	80
Water flow rate (kg/s)	2.30E-03	2.30E-03	2.29E-03
T1 (^{o}C)	29.89	29.5	29.26
T2 (^{o}C)	39	39.2	38.58
Condensate rate (kg/s)	2.49E-05	2.6E-05	2.58E-05
Air temperature (°C)	60	60	60
Q (kW)	0.088	0.093	0.089
dTm	25.56	25.65	26.08
U (kW/m^2 K)	0.287	0.305	0.287
Efficiency	0.69	0.68	0.70

7.2.1.3. Case of 90 Percent Relative Humidity and 18 (L/s) Flow Rate

40 minutes of data were collected and divided into 4 parts as shown in Table 7.3. Average efficiency value was found 90.5 percent. Efficiency values were lower than 70°C, 90 percent, 18 l/s meaning lowering air-stream mixture temperature lowered efficiency of condensation.

Table 7.3. 60°C, 90%, 18 l/s Results

	Exp7	**Exp8**	**Exp9**	**Exp10**
Air flow rate (l/s)	18	18	18	18
Air humidity (%)	90	90	90	90
Water flow rate (kg/s)	3.20E-03	3.19E-03	3.20E-03	3.18E-03
T1 (^{o}C)	30	29.67	29.72	29.49
T2 (^{o}C)	35.84	35.59	35.56	35.14
Condensate rate (kg/s)	3.05E-05	3.03E-05	2.88E-05	2.6E-05
Air temperature (°C)	60	60	60	60
Q (kW)	0.078	0.079	0.078	0.075
dTm	27.08	27.37	27.36	27.69
U (kW/m^2 K)	0.242	0.242	0.239	0.227
Efficiency	0.95	0.93	0.90	0.84

7.2.1.4. Case of 70 Percent Relative Humidity and 24 (L/s) Flow Rate

Average efficiency at the 60°C, 70 percent relative humidity and 24 l/s steam-air mixture flow rate experiments were found 49 percent. Lowest efficiency values were obtained at this setting in all experiments as 46 percent which can be seen in Table 7.4.

Table 7.4. 60°C, 70%, 24 l/s Results

	Exp11	**Exp12**	**Exp13**
Air flow rate (l/s)	24	24	24
Air humidity (%)	70	70	70
Water flow rate (kg/s)	2.28E-03	2.26E-03	2.29E-03
T1 (^{o}C)	30.22	30.16	30.01
T2 (^{o}C)	37.25	36.81	37.65
Condensate rate (kg/s)	1.28E-05	1.41E-05	1.42E-05
Air temperature (°C)	60	60	60

Q (kW)	0.067	0.063	0.073
dTm	25.82	26.52	26.04
U (kW/m^2 K)	0.218	0.199	0.235
Efficiency	0.46	0.54	0.47

7.2.1.5. Case of 80 Percent Relative Humidity 24 (L/s) Flow Rate

Table 7.5 shows results for case of 80 percent relative humidity and 24 l/s mixture flow rate. Average condensation efficiency was found 72.3 percent.

Table 7.5. 60°C, 80%, 24 l/s Results

	Exp14	**Exp15**	**Exp16**
Air flow rate (l/s)	24	24	24
Air humidity (%)	80	80	80
Water flow rate (kg/s)	2.27E-03	2.30E-03	2.28E-03
T1 (^{0}C)	29.94	29.86	29.59
T2 (^{0}C)	38.42	38.74	38.33
Condensate rate (kg/s)	2.52E-05	2.44E-05	2.46E-05
Air temperature (°C)	60	60	60
Q (kW)	0.080	0.085	0.083
dTm	27.21	27.72	26.04
U (kW/m^2 K)	0.248	0.258	0.268
Efficiency	0.76	0.69	0.72

7.2.1.6. Case of 90 Percent Relative Humidity 24 (L/s) Flow Rate

Results for case of 90 percent relative humidity and 24 l/s flow rate can be seen in Table 7.6. Highest condensation efficiency value was obtained as 106 percent and lowest condensation efficiency was obtained as 93 percent. 30 minutes of data were divided in to three 10 minute parts in order to calculate results.

Table 7.6. 60°C, 90%, 24 l/s Results

	Exp17	**Exp18**	**Exp19**
Air flow rate (l/s)	24	24	24
Air humidity (%)	90	90	90
Water flow rate (kg/s)	3.90E-03	3.89E-03	3.91E-03
T1 (^{0}C)	29.67	29.42	30.01
T2 (^{0}C)	35.91	35.15	35.13
Condensate rate (kg/s)	3.89E-05	3.72E-05	3.65E-05
Air temperature (°C)	60	60	60
Q (kW)	0.102	0.093	0.084
dTm	27.21	27.72	27.43
U (kW/m^2 K)	0.313	0.282	0.256
Efficiency	0.93	0.97	1.06

According to Figure 7.16 and 7.17, efficiency increases as humidity increases if process air temperature and flow rate kept constant. For mixture temperature of 60°C and relative humidity of 70 percent, average condensation efficiency decreases as the mixture flow rate increases while this can't be seen for relative humidity of 80 percent. Condensation efficiency value increases with increasing mixture flow rate for 90 percent humidity which is opposite of the results for 70 percent. Error bars with 95 percent confidence.

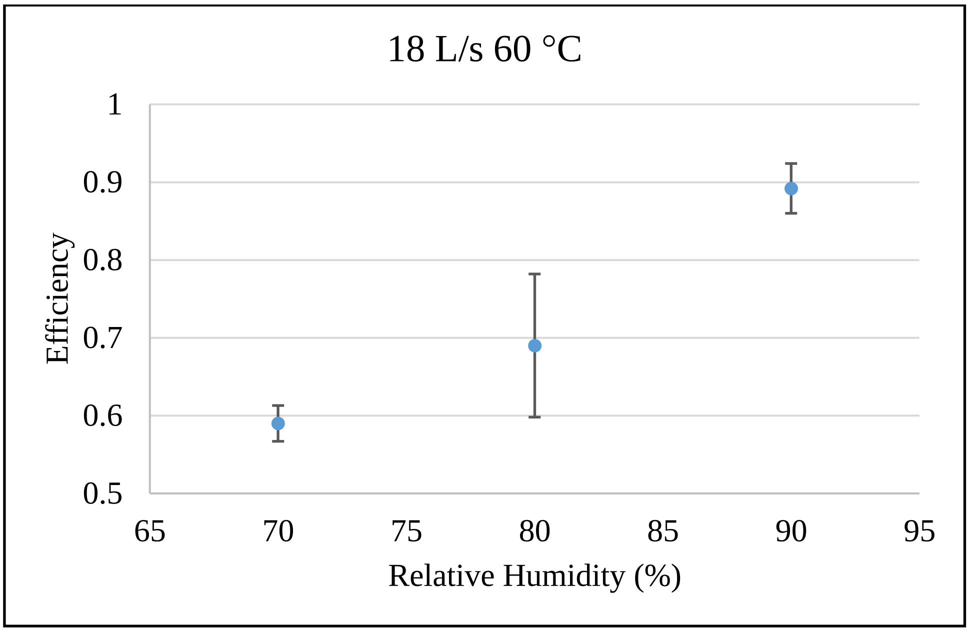

Figure 7.16. Relative humidity vs. efficiency for 18 l/s 60°C

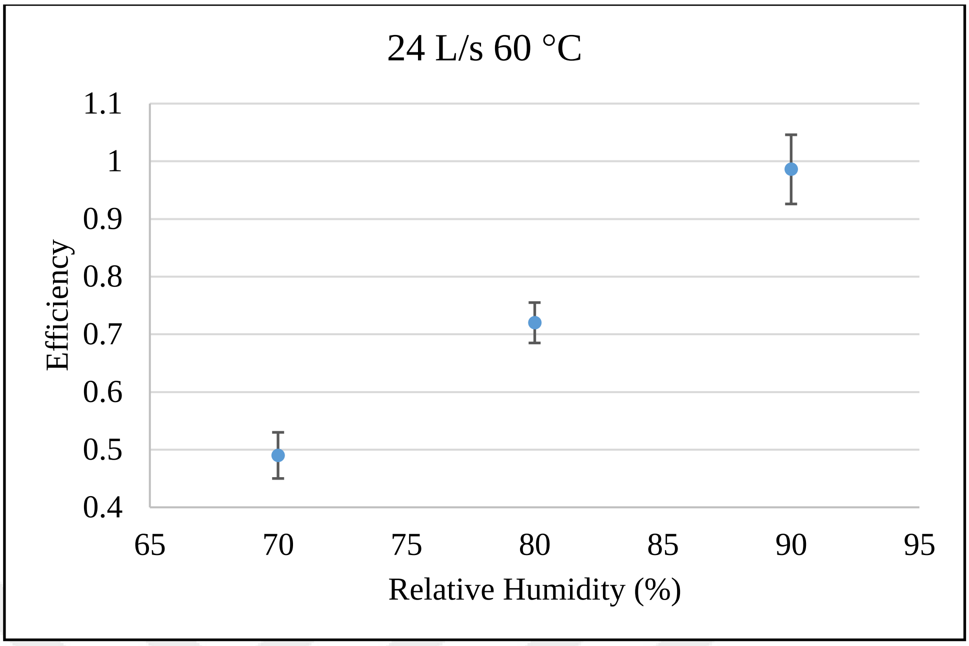

Figure 7.17. Relative humidity vs. efficiency for 24 l/s 60°C

7.2.2. Results of Humid Air Temperature at 70°C

7.2.2.1. Case of 70 Percent Relative Humidity and 18 (L/s) Flow Rate

During cylindrical condenser experiments, complete experimental data were divided into 10 minute parts for calculations. 40 minutes of data were collected for experiments 20 to 23 as shown in Table 7.7. Average efficiency was 81.2 percent.

Overall heat transfer coefficient results were lower than the flat plate condenser results at the same air-steam mixture temperature, flow rate and relative humidity values.

Table 7.7. 70°C, 70%, 18 l/s Results

	Exp20	**Exp21**	**Exp22**	**Exp23**
Air flow rate (l/s)	18	18	18	18
Air humidity (%)	70	70	70	70
Water flow rate (kg/s)	3.80E-03	3.89E-03	3.84E-03	3.83E-03
T1 (^{0}C)	31.1	31.1	30.86	30.7
T2 (^{0}C)	38.7	38.9	38.6	38.17
Condensate rate (kg/s)	3.93E-05	4.07E-05	4.17E-05	4.20E-05
Air temperature (°C)	70	70	70	70
Q (kW)	0.121	0.127	0.124	0.120
dTm	35.10	35.00	35.27	35.57
U (kW/m^2 K)	0.288	0.304	0.295	0.282
Efficiency	0.79	0.78	0.82	0.86

7.2.2.2. Case of 80 Percent Relative Humidity and 18 (L/s) Flow Rate

40 minutes of data were collected for experiments 24-27 as shown in Table 7.8. Evidently, increasing relative humidity increases efficiency for the cylindrical condenser.

Table 7.8. 70°C, 80%, 18 l/s Results

	Exp24	**Exp25**	**Exp26**	**Exp27**
Air flow rate (l/s)	18	18	18	18
Air humidity (%)	80	80	80	80
Water flow rate (kg/s)	3.87E-03	3.84E-03	3.86E-03	4.00E-03
T1 (^{0}C)	30.59	30.43	30.33	30.67
T2 (^{0}C)	38.6	38.58	37.76	37.2
Condensate rate (kg/s)	4.69E-05	4.55E-05	4.49E-05	4.29E-05
Air temperature (°C)	70	70	70	70
Q (kW)	0.130	0.131	0.120	0.109
dTm	35.41	35.50	35.96	36.07
U (kW/m^2 K)	0.307	0.309	0.279	0.254
Efficiency	0.88	0.85	0.91	0.96

7.2.2.3. Case of 70 Percent Relative Humidity and 24 (L/s) Flow Rate

50 minutes of data were collected for experiments 28-32. Average efficiency was found 73 percent. Compared to 70 percent humidity and 18 l/s air-steam mixture flow rate, heat transfer rates were lower. Results shown in Table 7.9.

Table 7.9. 70°C, 70%, 24 l/s Results

	Exp28	**Exp29**	**Exp30**	**Exp31**	**Exp32**
Air flow rate (l/s)	24	24	24	24	24
Air humidity (%)	70	70	70	70	70
Water flow rate (kg/s)	3.61E-03	3.60E-03	3.59E-03	3.62E-03	3.62E-03
T1 (^{0}C)	30.43	30.57	30.285	30	29.76
T2 (^{0}C)	37.75	37.06	37.55	37	36.69
Condensate rate (kg/s)	3.24E-05	3.11E-05	3.03E-05	3.19E-05	3.23E-05
Air temperature (°C)	70	70	70	70	70
Q (kW)	0.110	0.098	0.109	0.106	0.105
dTm	35.91	36.19	36.08	36.50	36.78
U (kW/m^2 K)	0.258	0.226	0.253	0.243	0.239
Efficiency	0.71	0.78	0.68	0.73	0.75

7.2.2.4. Case of 80 Percent Relative Humidity and 24 (L/s) Flow Rate

Average efficiency for 70°C, 80 percent relative humidity, 24 l/s was found 85.5 percent as seen in Table 7.10. While keeping mixture temperature and flow rate constant, efficiency increases as relative humidity increases for cylindrical condenser setup.

Table 7.10. 70°C, 80%, 24 l/s Results

	Exp33	Exp34	Exp35	Exp36	Exp37	Exp38
Air flow rate (l/s)	24	24	24	24	24	24
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	3.62E-03	3.60E-03	3.61E-03	3.59E-03	3.60E-03	3.60E-03
T1 (^{0}C)	29.96	29.7	29.63	29.63	29.57	29.74
T2 (^{0}C)	37.51	37.3	36.84	37.65	37.55	37.8
Condensate rate (kg/s)	3.9E-05	3.9E-05	4E-05	4.6E-05	4.08E-05	4.10E-05
Air temperature (°C)	70	70	70	70	70	70
Q (kW)	0.114	0.114	0.109	0.120	0.120	0.121
dTm	36.27	36.50	36.77	36.36	36.44	36.23
U (kW/m^2 K)	0.264	0.263	0.248	0.277	0.276	0.281
Efficiency	0.84	0.83	0.89	0.92	0.83	0.82

7.2.2.5. Case of 90 Percent Relative Humidity and 24 (L/s) Flow Rate

60 minutes of data were collected for experiments 39-44 as shown in Table 7.11. Experiments 21 and 24 exceeded 100 percent. Overall heat transfer coefficient was higher than 80 percent humidity while keeping air-steam mixture temperature and flow rate constant. Highest condensation efficiency of 108 percent was obtained for the cylindrical condenser setup.

Table 7.11. 70°C, 90%, 24 l/s Results

	Exp39	Exp40	Exp41	Exp42	Exp43	Exp44
Air flow rate (l/s)	24	24	24	24	24	24
Air humidity (%)	90	90	90	90	90	90
Water flow rate (kg/s)	3.61E-03	3.63E-03	3.62E-03	3.64E-03	3.61E-03	3.62E-03
T1 (^{0}C)	29.74	29.58	29.48	29.28	30.18	30.57
T2 (^{0}C)	39.01	38.6	38.44	38.63	38.19	39.6
Condensate rate (kg/s)	5.55E-05	5.68E-05	5.49E-05	5.59E-05	5.34E-05	5.51E-05
Air temperature (°C)	70	70	70	70	70	70
Q (kW)	0.140	0.137	0.136	0.142	0.121	0.137
dTm	35.63	35.91	36.04	36.05	35.82	34.92
U (kW/m^2 K)	0.329	0.319	0.315	0.331	0.283	0.328
Efficiency	0.97	1.01	0.99	0.96	1.08	0.98

7.2.2.6. Case of 90 Percent Relative Humidity and 18 (L/s) Flow Rate

Results for experiments 45-50 are shown below in Table 7.12. Highest condensation efficiency for this case was 105 percent.

Table 7.12. 70°C, 90%, 18 l/s Results

	Exp45	**Exp46**	**Exp47**	**Exp48**	**Exp49**	**Exp50**
Air flow rate (l/s)	18	18	18	18	18	18
Air humidity (%)	90	90	90	90	90	90
Water flow rate (kg/s)	4.08E-03	4.00E-03	4.10E-03	4.09E-03	4.10E-03	4.00E-03
T1 (^{0}C)	29.6	30.6	30.7	30.41	30.05	29.78
T2 (^{0}C)	38	38.85	38.72	38.62	38.9	38.2
Condensate rate (kg/s)	6.00E-05	5.95E-05	5.62E-05	5.63E-05	5.86E-05	5.75E-05
Air temperature (°C)	70	70	70	70	70	70
Q (kW)	0.143	0.138	0.137	0.140	0.152	0.141
dTm	36.20	35.28	35.29	35.49	35.53	36.01
U (kW/m^2 K)	0.332	0.328	0.326	0.332	0.358	0.328
Efficiency	1.02	1.05	1.00	0.98	0.94	0.99

Relative humidity vs. efficiency graph shows the relation between the two parameter. While keeping flow rate of steam-air mixture at 18 l/s and temperature at 70°C efficiency increases with increasing relative humidity. Same results were obtained for 24 l/s, where efficiency increased by increasing relative humidity as shown in Figure 7.19.

For both 18 l/s and 24 l/s results, general trend shows that condensation efficiency increases as relative humidity increases as seen in Figure 7.18 and Figure 7.19. Mixture flow rate of 18 l/s yields condensation efficiency of 81 percent at 70 percent humidity and the efficiency increases linearly to 99 percent at 90 percent humidity. During mixture flow rate of 24 l/s, condensation efficiencies were lower than 18 l/s at 70 percent and 80 percent humidity but 90 percent humidity results were close.

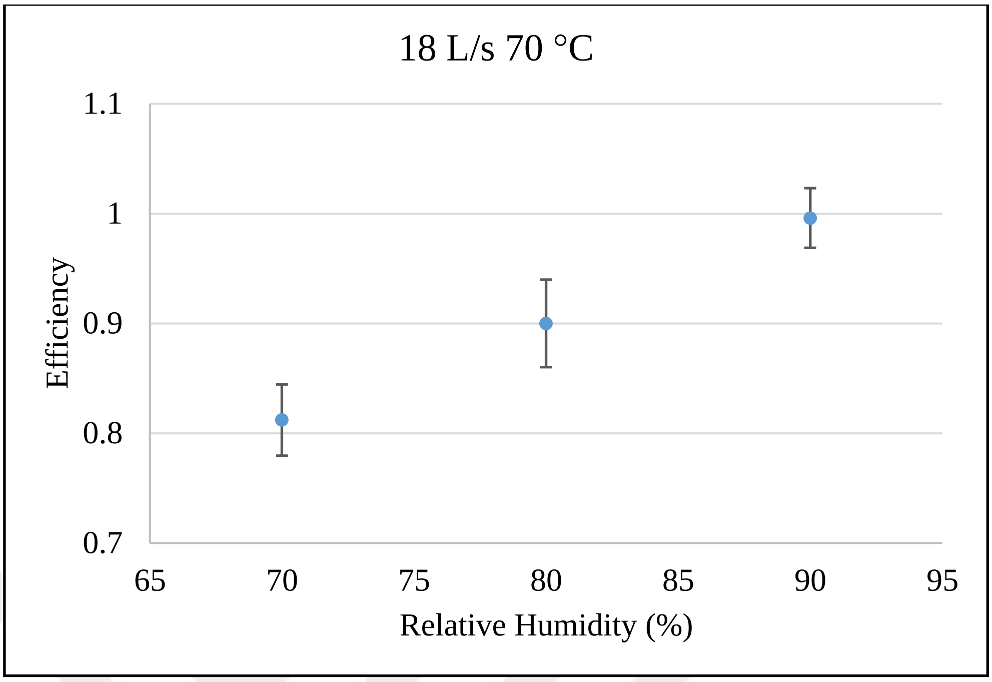

Figure 7.18. Relative Humidity vs. efficiency for 18 l/s 70°C

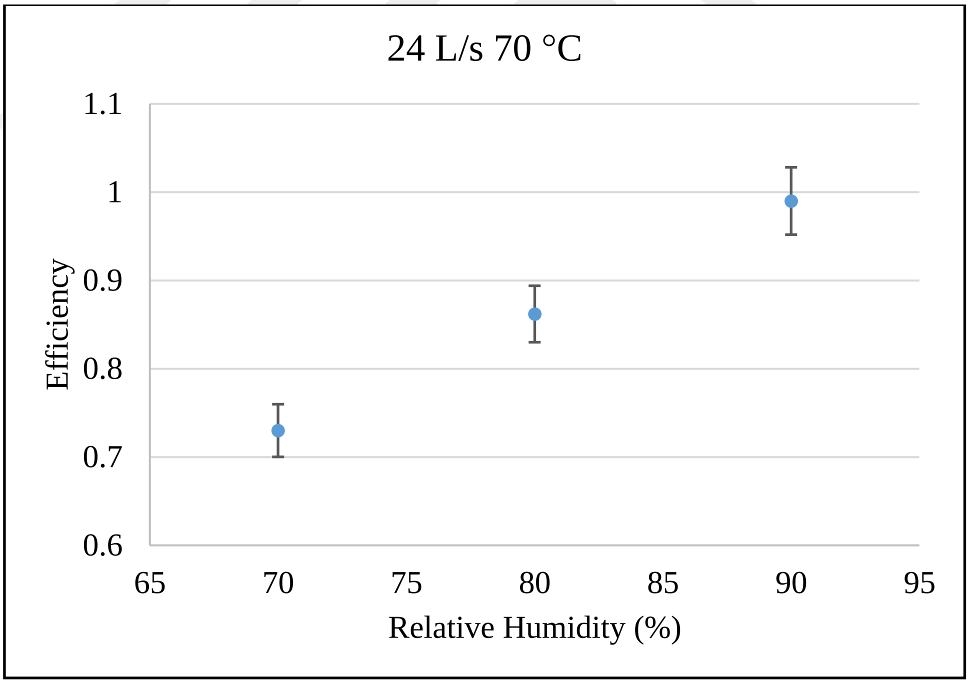

Figure 7.19. Relative Humidity vs. efficiency for 24 l/s 70°C

There is no visible trend in mixture flow rate vs. overall heat transfer coefficient results. In Figure 7.20, it can be seen that at 70 percent and 90 percent humidity, overall heat transfer coefficient increases with respect to mixture flow rate but this is not true for 80 percent humidity. In Figure 7.21, overall heat transfer coefficient decreases as air-steam mixture flow rate increases for all relative humidity values.

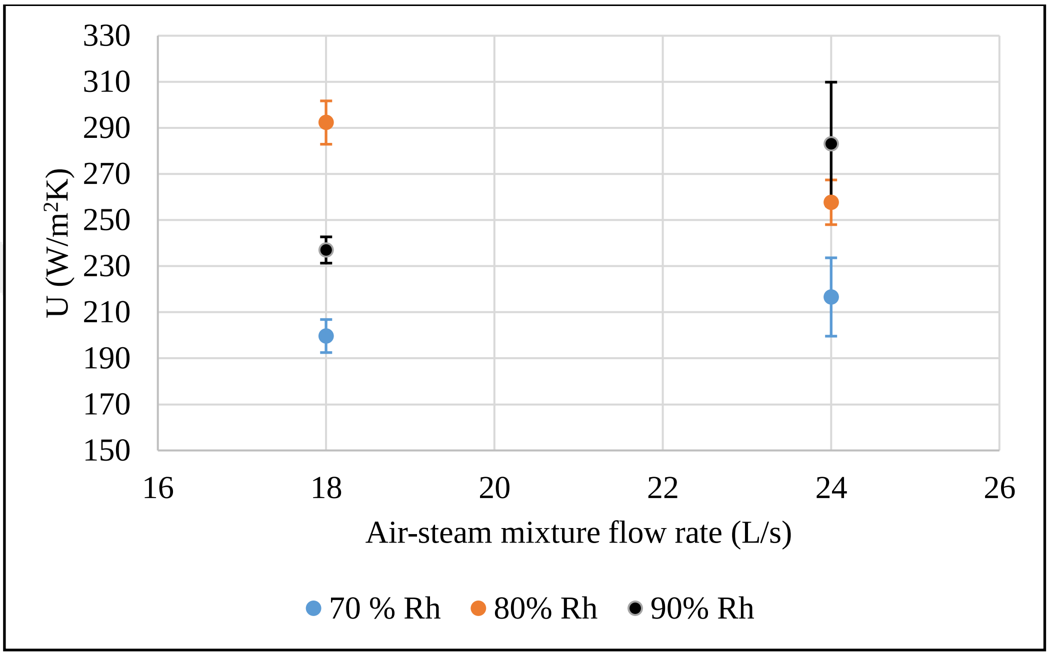

Figure 7.20. Mixture flow rate vs. U at 60°C

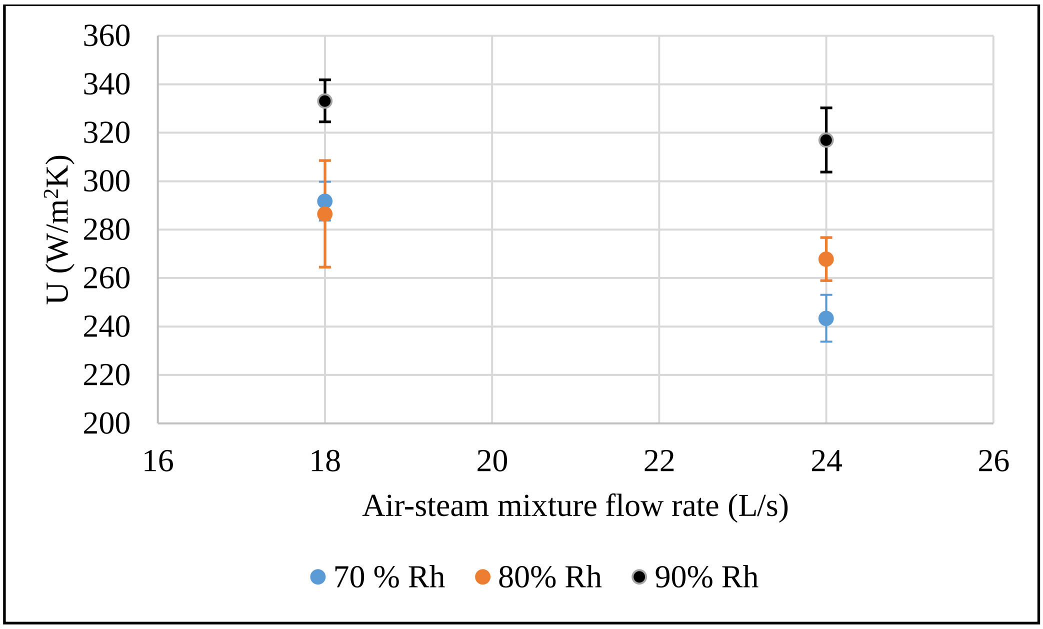

Figure 7.21. Mixture flow rate vs. U at 70°C

7.3. DISCUSSION

The use of the water tower instead of the pump only setup enabled to obtain constant cooling water flow rate during experiments with little change. Since the only way to measure cooling water flow rate was using a beaker and a stopwatch, it was crucial to reduce error by keeping the flow rate constant as much as possible during experiments. For flat plate experiments, switching to the water tower system made it possible to achieve constant surface temperature boundary conditions by employing a simple valve setup and keeping inlet and outlet temperatures within 5°C-8°C. Most of the uncertainty during experiments believed to be caused by hand movements during flow rate measurements. Switching to a closed loop system for cooling water was able to keep inlet temperatures at 29.9°C ± 0.053°C (±0.18 percent) for cylindrical condenser experiments which was another important change in the system. The experimental setup for both cylindrical and flat-plate condensers generally performed well during experiments. Thermocouples inside the flat plate condenser setup were not able to yield acceptable results because of their placement. Since first three thermocouples were placed deeper than the middle and inlet thermocouples, they were not able to show the surface temperature accurately. In comparison with the earlier work done by Ahn et al. [12], the condensation efficiency in the present study increased with respect to increasing air-steam mixture humidity and cooling water temperature. Increasing mixture flow rate increased overall heat transfer coefficient in flat plate condenser setup and increasing cooling water temperature decreased overall heat transfer coefficient.

8. CONCLUSION

Steam condensation in the presence of non-condensable air has been experimentally investigated in cross-flow flat-plate and cross-flow cylindrical condenser in which water was employed as cooling fluid. Condensation efficiency for both setups were investigated as a function of inlet, outlet conditions and dimensions of both condensers. By employing a thermostat and a water heater setup, cooling water inlet temperature was stable at 30°C for both flat-plate and cylindrical condensers. Using a water tower setup instead of the pump-only system helped keeping the cooling water fluid flow rate constant during the experiments. Experiments with the cylindrical condenser were conducted at the steam-air mixture flow rates of 18 l/s and 24 l/s while the flat-plate condenser experiments were conducted for 12, 16 and 20 l/s mixture flow rates. For the case of cylindrical condenser, air-steam mixture temperature values were 60°C and 70°C and for flat plate condenser, air-vapor mixture temperature was set to 70°C and cooling water temperatures were 30°C, 35°C and 40°C. For the flat-plate condenser, air-steam mixture flow channel height was set to 10 mm. For both condensers, the efficiency of condensation increased with increasing air-steam mixture temperature and relative humidity. Increasing cooling water temperature increased condensation efficiency in flat plate condenser setup.

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APPENDIX A : FLAT PLATE EXPERIMENTAL RESULTS

Table A.1. 12 l/s, 60%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp1	**Exp2**	**Exp3**	**Exp4**	**Exp5**	**Exp6**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0109	0.0109	0.0109	0.0109	0.0109	0.0109
T1 (^{0}C)	30.34	30.35	30.23	30.00	30.33	30.39
T2 (^{0}C)	36.73	36.82	36.77	36.67	36.82	37.04
Condensate rate (kg/s)	0.000075	0.000079	0.000072	0.000081	0.000077	0.000077
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	65.66	65.76	65.96	66.22	66.35	66.33
Mixture outlet temperature (°C)	59.37	59.36	59.32	59.37	59.38	59.38
Q (W)	291.4	294.8	297.9	303.9	295.7	303.1
LMTD	28.51	28.49	28.63	28.94	28.77	28.60
U (W/m^{2}K)	255.5	258.7	260.1	262.5	257.0	265.0
Efficiency	0.63	0.65	0.59	0.65	0.64	0.62

Table A.2. 16 l/s, 60%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp7	**Exp8**	**Exp9**	**Exp10**	**Exp11**	**Exp12**
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0109	0.0109	0.0109	0.0109	0.0109	0.0109
T1 (^{0}C)	30.56	30.44	30.35	30.13	29.93	30.28
T2 (^{0}C)	37.80	37.76	37.76	37.49	37.40	37.58
Condensate rate (kg/s)	0.000089	0.000086	0.000090	0.000087	0.000090	0.000092
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	66.85	66.88	66.90	66.93	66.95	66.91
Mixture outlet temperature (°C)	60.42	60.48	60.48	60.47	60.53	60.41
Q (W)	330.0	333.4	337.6	335.4	340.7	332.8
LMTD	28.92	29.04	29.09	29.35	29.53	29.19
U (W/m^{2}K)	285.3	287.0	290.1	285.6	288.5	285.0
Efficiency	0.66	0.63	0.65	0.63	0.64	0.67

Table A.3. 20 l/s, 60%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp13	**Exp14**	**Exp15**	**Exp16**	**Exp17**	**Exp18**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138
T1 (^{0}C)	30.29	30.11	29.94	30.32	30.71	30.54
T2 (^{0}C)	36.78	36.64	36.48	36.64	36.86	36.74
Condensate rate (kg/s)	0.000094	0.000090	0.000092	0.000091	0.000089	0.000087
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.19	67.22	67.21	67.26	67.27	67.28
Mixture outlet temperature (°C)	61.24	61.24	61.21	61.16	61.21	61.21
Q (W)	374.2	376.7	376.9	364.5	354.4	358.0
LMTD	30.26	30.43	30.57	30.31	30.04	30.19
U (W/m^{2}K)	309.2	309.5	308.2	300.7	294.9	296.5
Efficiency	0.61	0.58	0.60	0.61	0.61	0.59

Table A.4. 12 l/s, 60%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp19	**Exp20**	**Exp21**	**Exp22**	**Exp23**	**Exp24**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0084	0.0084	0.0084	0.0084	0.0084	0.0084
T1 (^{0}C)	35.27	35.03	35.06	35.22	35.00	34.93
T2 (^{0}C)	42.45	42.37	42.28	42.40	42.31	42.28
Condensate rate (kg/s)	0.000075	0.000073	0.000075	0.000079	0.000078	0.000080
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.00	66.88	66.91	66.94	66.85	66.91
Mixture outlet temperature (°C)	60.71	60.63	60.48	60.57	60.53	60.49
Q (W)	252.0	257.8	253.8	252.2	257.9	258.0
LMTD	24.38	24.43	24.39	24.32	24.41	24.45
U (W/m^{2}K)	258.4	263.8	260080.0	259.2	264.2	263.8
Efficiency	0.72	0.69	0.72	0.76	0.74	0.76

Table A.5. 16 l/s, 60%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp25	**Exp26**	**Exp27**	**Exp28**	**Exp29**	**Exp30**
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0084	0.0084	0.0084	0.0084	0.0084	0.0084
T1 (^{0}C)	35.08	35.03	35.30	35.07	34.92	35.26
T2 (^{0}C)	42.63	42.65	42.97	42.84	42.79	42.99
Condensate rate (kg/s)	0.000079	0.000079	0.000080	0.000076	0.000082	0.000080
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.28	67.23	67.19	67.18	67.22	67.17
Mixture outlet temperature (°C)	61.49	61.37	61.36	61.37	61.39	61.37
Q (W)	265.1	267.6	269.3	273.0	276.3	271.2
LMTD	24.94	24.85	24.53	24.70	24.82	24.53
U (W/m^{2}K)	265.7	269.1	274.5	276.3	278.3	276.4
Efficiency	0.72	0.72	0.72	0.68	0.73	0.72

Table A.6. 20 l/s, 60%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp31	**Exp32**	**Exp33**	**Exp34**	**Exp35**	**Exp36**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0084	0.0084	0.0084	0.0084	0.0084	0.0084
T1 (^{0}C)	35.03	35.17	35.26	35.26	35.08	34.95
T2 (^{0}C)	43.28	43.15	43.13	43.17	43.10	42.97
Condensate rate (kg/s)	0.000088	0.000088	0.000084	0.000083	0.000085	0.000087
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.45	67.46	67.45	67.48	67.49	67.51
Mixture outlet temperature (°C)	62.26	62.14	62.12	62.12	62.12	62.05
Q (W)	290.0	280.0	276.5	277.5	281.6	281.8
LMTD	25.10	25.06	25.01	25.01	25.12	25.22
U (W/m^{2}K)	288.8	279.3	276.3	277.4	280.3	279.3
Efficiency	0.74	0.76	0.74	0.73	0.74	0.75

Table A.7. 12 l/s, 60%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp37	Exp38	Exp39	Exp40	Exp41	Exp42
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087
T1 (^{0}C)	39.92	40.19	40.26	39.91	40.09	40.36
T2 (^{0}C)	45.31	45.23	45.26	45.09	45.03	45.29
Condensate rate (kg/s)	0.000063	0.000059	0.000056	0.000056	0.000057	0.000054
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	66.97	67.00	67.02	66.99	66.96	66.98
Mixture outlet temperature (°C)	61.12	60.94	60.95	61.00	60.91	60.97
Q (W)	196.1	183.1	181.9	188.5	179.7	179.4
LMTD	20.93	20.77	20.74	21.00	20.90	20.67
U (W/m^{2}K)	234.2	220.3	219.3	224.3	214.9	217.0
Efficiency	0.78	0.78	0.75	0.72	0.77	0.74

Table A.8. 16 l/s, 60%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp43	Exp44	Exp45	Exp46	Exp47	Exp48
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087
T1 (^{0}C)	39.99	40.41	40.35	39.91	40.26	40.34
T2 (^{0}C)	45.64	45.80	45.62	45.25	45.63	45.75
Condensate rate (kg/s)	0.000062	0.000058	0.000054	0.000055	0.000056	0.000059
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.26	67.27	67.28	67.32	67.30	67.24
Mixture outlet temperature (°C)	61.69	61.76	61.73	61.67	61.80	61.83
Q (W)	205.6	196.2	191.4	194.1	195.3	197.0
LMTD	21.17	20.94	21.06	21.45	21.14	21.03
U (W/m^{2}K)	242.8	234.2	227.3	226.2	231.0	234.1
Efficiency	0.74	0.72	0.69	0.69	0.70	0.72

Table A.9. 20 l/s, 60%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp49	**Exp50**	**Exp51**	**Exp52**	**Exp53**	**Exp54**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087
T1 (^{0}C)	40.20	40.35	40.02	40.07	40.38	40.22
T2 (^{0}C)	45.98	46.16	45.85	45.74	46.06	45.91
Condensate rate (kg/s)	0.000050	0.000049	0.000046	0.000044	0.000046	0.000044
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.47	67.45	67.48	67.54	67.57	67.52
Mixture outlet temperature (°C)	62.31	62.35	62.35	62.39	62.54	62.52
Q (W)	210.1	211.4	212.0	206.3	206.5	207.1
LMTD	21.34	21.18	21.51	21.61	21.39	21.51
U (W/m^{2}K)	246.2	249.5	246.4	238.6	241.3	240.7
Efficiency	0.58	0.56	0.52	0.52	0.54	0.52

Table A.10. 12 l/s, 70%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp55	**Exp56**	**Exp57**	**Exp58**	**Exp59**	**Exp60**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0236	0.0236	0.0236	0.0236	0.0236	0.0236
T1 (^{0}C)	30.76	30.67	30.66	30.68	30.68	30.68
T2 (^{0}C)	35.77	35.71	35.67	35.73	35.67	35.70
Condensate rate (kg/s)	0.000175	0.000173	0.000175	0.000178	0.000166	0.000174
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.29	67.28	67.27	67.25	67.23	67.30
Mixture outlet temperature (°C)	61.15	61.08	61.08	61.11	61.08	61.16
Q (W)	494.1	496.5	494.3	498.1	491.7	495.7
LMTD	30.62	30.65	30.67	30.64	30.64	30.70
U (W/m^{2}K)	403.4	405.0	402.9	406.4	401.2	403.7
Efficiency	0.86	0.85	0.86	0.87	0.82	0.85

Table A.11. 16 l/s, 70%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp61	**Exp62**	**Exp63**	**Exp64**	**Exp65**	**Exp66**
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0236	0.0236	0.0236	0.0236	0.0236	0.0236
T1 (^{0}C)	30.71	30.70	30.72	30.71	30.71	30.66
T2 (^{0}C)	36.42	36.35	36.38	36.40	36.37	36.34
Condensate rate (kg/s)	0.000190	0.000189	0.000186	0.000195	0.000193	0.000184
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.55	67.60	67.61	67.60	67.64	67.70
Mixture outlet temperature (°C)	61.98	62.01	62.00	62.08	62.05	62.13
Q (W)	562.5	556.9	558.1	561.2	558.5	560.6
LMTD	30.86	30.94	30.91	30.95	30.97	31.08
U (W/m^{2}K)	455.7	449.9	451.3	453.3	450.9	451.0
Efficiency	0.82	0.82	0.81	0.84	0.84	0.80

Table A.12. 20 l/s, 70%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp67	**Exp68**	**Exp69**	**Exp70**	**Exp71**	**Exp72**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0236	0.0236	0.0236	0.0236	0.0236	0.0236
T1 (^{0}C)	30.77	30.75	30.70	30.70	30.68	30.77
T2 (^{0}C)	37.13	37.05	36.99	37.06	37.05	37.09
Condensate rate (kg/s)	0.000204	0.000207	0.000205	0.000208	0.000207	0.000209
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.71	67.74	67.69	67.73	67.72	67.71
Mixture outlet temperature (°C)	62.58	62.52	62.39	62.43	62.45	62.41
Q (W)	627.0	621.5	621.2	627.4	628.1	623.4
LMTD	30.84	30.88	30.83	30.83	30.86	30.77
U (W/m^{2}K)	508.2	503.2	503.8	508.7	508.9	506.6
Efficiency	0.79	0.81	0.81	0.81	0.80	0.82

Table A.13. 12 l/s, 70%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp73	**Exp74**	**Exp75**	**Exp76**	**Exp77**	**Exp78**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177
T1 (^{0}C)	35.44	35.28	35.57	35.54	35.31	35.35
T2 (^{0}C)	41.03	40.88	41.11	41.08	40.94	40.92
Condensate rate (kg/s)	0.000146	0.000146	0.000134	0.000138	0.000141	0.000139
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.34	67.30	67.36	67.34	67.36	67.32
Mixture outlet temperature (°C)	62.06	62.01	62.06	62.07	62.05	61.93
Q (W)	413.4	414.3	409.7	410.1	416.6	412.1
LMTD	26.08	26.20	25.99	26.02	26.20	26.11
U (W/m^{2}K)	396.2	395.2	394.0	394.0	397.5	394.6
Efficiency	0.86	0.86	0.80	0.82	0.82	0.82

Table A.14. 16 l/s, 70%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp79	**Exp80**	**Exp81**	**Exp82**	**Exp83**	**Exp84**
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177
T1 (^{0}C)	35.36	35.65	35.63	35.36	35.49	35.61
T2 (^{0}C)	41.88	42.01	41.86	41.71	41.75	41.82
Condensate rate (kg/s)	0.000160	0.000149	0.000154	0.000154	0.000149	0.000147
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.65	67.58	67.67	67.60	67.64	67.66
Mixture outlet temperature (°C)	62.76	62.58	62.65	62.58	62.50	62.56
Q (W)	482.7	470.6	461.5	469.8	463.2	459.3
LMTD	26.17	25.84	26.01	26.14	26.03	25.98
U (W/m^{2}K)	461.1	455.4	443.6	449.3	444.9	441.9
Efficiency	0.81	0.77	0.81	0.80	0.78	0.78

Table A.15. 20 l/s, 70%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp85	**Exp86**	**Exp87**	**Exp88**	**Exp89**	**Exp90**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177
T1 (^{0}C)	35.55	35.71	35.54	35.29	35.61	35.56
T2 (^{0}C)	42.47	42.55	42.47	42.29	42.52	42.58
Condensate rate (kg/s)	0.000165	0.000170	0.000165	0.000172	0.000177	0.000157
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.92	67.90	67.87	67.85	67.91	67.89
Mixture outlet temperature (°C)	63.04	63.02	63.01	63.00	63.03	63.05
Q (W)	512.2	506.5	512.3	517.8	511.8	519.4
LMTD	26.03	25.89	25.99	26.19	25.96	25.96
U (W/m^{2}K)	491.9	489.1	492.8	494.3	492.9	500.2
Efficiency	0.79	0.82	0.78	0.81	0.84	0.73

Table A.16. 12 l/s, 70%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp91	**Exp92**	**Exp93**	**Exp94**	**Exp95**	**Exp96**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
T1 (^{0}C)	39.81	39.74	39.84	39.71	39.80	39.43
T2 (^{0}C)	45.22	44.97	44.72	45.23	46.31	46.45
Condensate rate (kg/s)	0.000063	0.000073	0.000055	0.000077	0.000087	0.000077
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	66.49	66.33	66.08	66.38	67.15	66.73
Mixture outlet temperature (°C)	61.35	61.11	60.79	61.11	61.93	61.67
Q (W)	210.5670141	203.23492	189.736284	214.88754	252.98127	272.78711
LMTD	20.97	20.93	20.75	20.81	20.94	20.68
U (W/m^{2}K)	251.0746345	242.78987	228.640035	258.19358	302.07431	329.84177
Efficiency	0.73	0.87	0.71	0.87	0.84	0.69

Table A.17. 16 l/s, 70%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp97	**Exp98**	**Exp99**	**Exp100**	**Exp101**	**Exp102**
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118
T1 (^{0}C)	40.29	40.03	39.94	40.38	40.25	39.91
T2 (^{0}C)	46.73	46.68	46.39	46.39	46.21	45.92
Condensate rate (kg/s)	0.000114	0.000124	0.000114	0.000106	0.000104	0.000102
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.67	67.67	67.75	67.63	67.59	67.52
Mixture outlet temperature (°C)	62.92	62.95	62.87	62.67	62.62	62.49
Q (W)	317.1	327.6	317.5	295.7	293.3	295.9
LMTD	21.30	21.46	21.65	21.30	21.41	21.62
U (W/m^{2}K)	372.2	381.7	366.6	347.1	342.5	342.1
Efficiency	0.88	0.92	0.87	0.88	0.86	0.84

Table A.18. 20 l/s, 70%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp103	**Exp104**	**Exp105**	**Exp106**	**Exp107**	**Exp108**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0117	0.0117	0.0117	0.0117	0.0117	0.0117
T1 (^{0}C)	39.80	40.24	40.38	39.84	40.44	40.05
T2 (^{0}C)	46.98	47.08	47.32	46.87	47.17	47.00
Condensate rate (kg/s)	0.000129	0.000117	0.000123	0.000125	0.000119	0.000121
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.82	67.79	67.81	67.80	67.79	67.79
Mixture outlet temperature (°C)	63.32	63.22	63.31	63.21	63.21	63.25
Q (W)	351.0	334.2	339.4	343.7	329.0	339.7
LMTD	21.66	21.34	21.19	21.63	21.20	21.48
U (W/m^{2}K)	405.2	391.4	400.3	397.3	388.0	395.4
Efficiency	0.90	0.86	0.88	0.89	0.88	0.87

Table A.19. 12 l/s, 80%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp109	Exp110	Exp111	Exp112	Exp113	Exp114
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0393	0.0393	0.0393	0.0393	0.0393	0.0393
T1 (^{0}C)	30.61	30.76	31.01	31.25	31.48	31.69
T2 (^{0}C)	35.33	35.44	35.65	35.82	35.98	36.09
Condensate rate (kg/s)	0.000249	0.000242	0.000241	0.000227	0.000228	0.000223
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	68.04	67.99	67.95	67.97	67.93	67.96
Mixture outlet temperature (°C)	63.66	63.62	63.55	63.55	63.50	63.52
Q (W)	775.8	769.0	762.8	750.3	740.1	724.0
LMTD	32.67	32.50	32.21	32.02	31.78	31.64
U (W/m^{2}K)	593.7	591.5	592.0	585.9	582.2	572.0
Efficiency	0.78	0.77	0.77	0.74	0.75	0.75

Table A.20. 16 l/s, 80%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp115	Exp116	Exp117	Exp118	Exp119	Exp120
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0393	0.0393	0.0393	0.0393	0.0393	0.0393
T1 (^{0}C)	30.46	30.41	30.46	30.45	30.49	30.42
T2 (^{0}C)	35.49	35.56	35.65	35.59	35.60	35.73
Condensate rate (kg/s)	0.000267	0.000275	0.000267	0.000279	0.000265	0.000277
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	68.04	68.01	68.01	68.03	68.00	68.03
Mixture outlet temperature (°C)	63.25	63.33	63.37	63.42	63.36	63.40
Q (W)	826.5	846.9	853.6	844.8	838.9	872.2
LMTD	32.42	32.44	32.39	32.46	32.39	32.39
U (W/m^{2}K)	637.4	652.8	658.9	650.7	647.4	673.2
Efficiency	0.79	0.79	0.76	0.80	0.77	0.77

Table A.21. 20 l/s, 80%, 70^{0}C experiments at 30^{0}C cooling fluid temperature

	Exp121	**Exp122**	**Exp123**	**Exp124**	**Exp125**	**Exp126**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0393	0.0393	0.0393	0.0393	0.0393	0.0393
T1 (^{0}C)	30.45	30.45	30.60	30.95	31.14	31.17
T2 (^{0}C)	36.20	36.14	36.16	36.55	36.75	36.79
Condensate rate (kg/s)	0.000304	0.000316	0.000307	0.000312	0.000305	0.000306
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	68.11	68.10	68.10	68.15	68.17	68.18
Mixture outlet temperature (°C)	63.57	63.52	63.51	63.57	63.61	63.64
Q (W)	944.9	933.8	914.7	921.0	921.4	922.4
LMTD	32.24	32.24	32.16	31.84	31.68	31.66
U (W/m^2K)	732.6	724.1	711.1	723.1	727.2	728.4
Efficiency	0.78	0.82	0.82	0.83	0.81	0.81

Table A.22. 12 l/s, 80%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp127	**Exp128**	**Exp129**	**Exp130**	**Exp131**	**Exp132**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0264	0.0264	0.0264	0.0264	0.0264	0.0264
T1 (^{0}C)	35.01	34.99	35.28	35.27	35.23	35.15
T2 (^{0}C)	40.41	40.40	40.63	40.71	40.66	40.57
Condensate rate (kg/s)	0.000211	0.000204	0.000211	0.000206	0.000200	0.000206
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.86	67.83	67.80	67.81	67.76	67.79
Mixture outlet temperature (°C)	63.49	63.43	63.40	63.44	63.41	63.35
Q (W)	596.0	596.9	591.1	600.5	599.9	598.0
LMTD	27.67	27.65	27.35	27.35	27.35	27.41
U (W/m^2K)	538.4	539.7	540.2	549.0	548.4	545.5
Efficiency	0.86	0.83	0.87	0.84	0.81	0.84

Table A.23. 16 l/s, 80%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp133	Exp134	Exp135	Exp136	Exp137	Exp138
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0264	0.0264	0.0264	0.0264	0.0264	0.0264
T1 (^{0}C)	34.95	35.24	35.30	35.25	35.31	35.25
T2 (^{0}C)	41.16	41.32	41.36	41.32	41.38	41.34
Condensate rate (kg/s)	0.000240	0.000233	0.000230	0.000234	0.000238	0.000237
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.95	68.02	68.01	67.97	68.00	68.08
Mixture outlet temperature (°C)	63.70	63.74	63.71	63.68	63.69	63.73
Q (W)	685364.7	670.6	668.0	669.7	669.4	672.5
LMTD	27.44	27.27	27.20	27.21	27.17	27.28
U (W/m^{2}K)	624.5	614.8	613.9	615.3	615.9	616.3
Efficiency	0.85	0.85	0.84	0.85	0.87	0.86

Table A.24. 20 l/s, 80%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp139	Exp140	Exp141	Exp142	Exp143	Exp144
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0264	0.0264	0.0264	0.0264	0.0264	0.0264
T1 (^{0}C)	35.33	35.31	35.19	35.09	35.00	34.96
T2 (^{0}C)	42.00	42.03	41.95	41.83	41.78	41.79
Condensate rate (kg/s)	0.000253	0.000258	0.000252	0.000250	0.000255	0.000260
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	68.04	68.08	68.03	68.04	68.03	68.02
Mixture outlet temperature (°C)	64.02	64.13	64.04	64.06	64.07	64.01
Q (W)	736.5	740.8	745.7	743.8	748.2	753.7
LMTD	27.01	27.08	27.11	27.24	27.31	27.28
U (W/m^{2}K)	681.5	683.8	687.6	682.7	684.9	690.8
Efficiency	0.84	0.85	0.82	0.82	0.83	0.84

Table A.25. 12 l/s, 80%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp145	Exp146	Exp147	Exp148	Exp149	Exp150
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0169	0.0169	0.0169	0.0169	0.0169	0.0169
T1 (^{0}C)	40.13	39.92	39.71	40.03	39.99	39.99
T2 (^{0}C)	46.47	46.21	45.56	45.81	45.52	45.33
Condensate rate (kg/s)	0.000157	0.000159	0.000145	0.000155	0.000136	0.000125
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.74	67.74	67.73	67.74	67.67	67.56
Mixture outlet temperature (°C)	64.12	64.02	63.76	63.67	63.47	63.38
Q (W)	449.0	445.7	414.0	409.2	391.6	377.5
LMTD	22.25	22.44	22.76	22.42	22.46	22.47
U (W/m^{2}K)	504.4	496.4	454.8	456.3	435.8	419.9
Efficiency	0.85	0.87	0.85	0.92	0.84	0.80

Table A.26. 16 l/s, 80%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp151	Exp152	Exp153	Exp154	Exp155	Exp156
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0169	0.0169	0.0169	0.0169	0.0169	0.0169
T1 (^{0}C)	39.94	39.71	39.97	40.00	40.02	39.88
T2 (^{0}C)	46.33	46.11	46.36	46.52	46.60	46.63
Condensate rate (kg/s)	0.000162	0.000160	0.000158	0.000172	0.000162	0.000179
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.94	67.85	67.89	67.85	67.95	67.93
Mixture outlet temperature (°C)	64.08	63.95	64.03	64.07	64.24	64.31
Q (W)	451.6	453.4	452.1	461.3	465.5	477.6
LMTD	22.49	22.60	22.41	22.31	22.39	22.46
U (W/m^{2}K)	502.0	501.5	504.4	516.9	519.7	531.6
Efficiency	0.87	0.86	0.85	0.91	0.85	0.91

Table A.27. 20 l/s, 80%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp157	**Exp158**	**Exp159**	**Exp160**	**Exp161**	**Exp162**
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	80	80	80	80	80	80
Water flow rate (kg/s)	0.0169	0.0169	0.0169	0.0169	0.0169	0.0169
T1 (^{0}C)	40.05	40.02	39.95	39.94	39.80	39.67
T2 (^{0}C)	47.73	47.59	47.59	47.64	47.50	47.42
Condensate rate (kg/s)	0.000197	0.000201	0.000211	0.000191	0.000204	0.000208
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	68.11	68.10	68.11	68.12	68.08	68.12
Mixture outlet temperature (°C)	64.66	64.63	64.65	64.69	64.63	64.65
Q (W)	543.3	536.1	540.7	544.7	545.3	548.3
LMTD	22.03	22.10	22.15	22.15	22.24	22.38
U (W/m^{2}K)	616.4	606.4	610.3	614.7	612.9	612.6
Efficiency	0.88	0.92	0.95	0.85	0.91	0.93

Table A.28. 12 l/s, 70%, 70^{0}C experiments at 30^{0}C cooling fluid temperature(repeated experiments).

	Exp163	**Exp164**	**Exp165**	**Exp166**	**Exp167**	**Exp168**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0162	0.0162	0.0162	0.0162	0.0162	0.0162
T1 (^{0}C)	30.41	30.44	30.42	30.47	30.37	30.27
T2 (^{0}C)	36.96	37.30	36.90	36.55	36.48	36.66
Condensate rate (kg/s)	0.000152	0.000151	0.000144	0.000126	0.000142	0.000150
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.20	67.24	67.16	67.06	67.16	67.15
Mixture outlet temperature (°C)	61.07	61.28	61.12	60.82	60.82	60.86
Q (W)	443.8	464.6	439.1	412.2	413.8	432.4
LMTD	30.01	29.93	30.05	30.01	30.14	30.10
U (W/m^{2}K)	369.7	388.0	365.4	343.4	343.3	359.1
Efficiency	0.83	0.79	0.80	0.74	0.83	0.84

Table A.29. 16 l/s, 70%, 70^{0}C experiments at 35^{0}C cooling fluid temperature(repeated experiments).

	Exp169	**Exp170**	**Exp171**	**Exp172**	**Exp173**	**Exp174**
Air flow rate (l/s)	16	16	16	16	16	16
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.015532	0.015532	0.015532	0.015532	0.015532	0.015532
T1 (^{0}C)	35.28	35.07	35.02	35.24	35.19	34.93
T2 (^{0}C)	42.29	42.02	42.06	42.32	42.37	42.12
Condensate rate (kg/s)	0.000146	0.000142	0.000145	0.000143	0.000145	0.000144
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.64	67.61	67.63	67.58	67.68	67.59
Mixture outlet temperature (°C)	62.49	62.42	62.37	62.44	62.51	62.39
Q (W)	454.9	451.2	457.2	459.3	466.2	467.0
LMTD	25.80	26.00	25.98	25.75	25.82	25.98
U (W/m^{2}K)	440.8	433.8	439.9	445.9	451.3	449.4
Efficiency	0.78	0.76	0.77	0.76	0.76	0.75

Table A.30. 12 l/s, 70%, 70^{0}C experiments at 40^{0}C cooling fluid temperature(repeated experiments).

	Exp175	**Exp176**	**Exp177**	**Exp178**	**Exp179**	**Exp180**
Air flow rate (l/s)	12	12	12	12	12	12
Air humidity (%)	70	70	70	70	70	70
Water flow rate (kg/s)	0.0107	0.0107	0.0107	0.0107	0.0107	0.0107
T1 (^{0}C)	39.83	39.49	39.73	39.77	39.41	39.85
T2 (^{0}C)	46.26	46.06	46.21	46.34	46.08	46.36
Condensate rate (kg/s)	0.000090	0.000085	0.000089	0.000085	0.000091	0.000095
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.56	67.62	67.54	67.60	67.54	67.58
Mixture outlet temperature (°C)	62.57	62.56	62.63	62.68	62.50	62.58
Q (W)	287.4	293.4	289.9	293.9	298.5	291.1
LMTD	21.52	21.80	21.62	21.58	21.75	21.46
U (W/m^{2}K)	333.9	336.5	335.3	340.6	343.1	339.0
Efficiency	0.77	0.70	0.75	0.71	0.74	0.79

Table A.31. 12 l/s, 60%, 70^{0}C experiments at 40^{0}C cooling fluid temperature(repeated experiments).

	Exp181	Exp182	Exp183	Exp184	Exp185	Exp186
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.01029	0.01029	0.01029	0.01029	0.01029	0.01029
T1 (^{0}C)	39.70	39.71	39.43	39.83	39.41	39.72
T2 (^{0}C)	45.73	45.74	45.41	45.79	45.49	45.79
Condensate rate (kg/s)	0.000060	0.000059	0.000055	0.000054	0.000056	0.000054
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.66	67.66	67.62	67.63	67.61	67.59
Mixture outlet temperature (°C)	62.84	62.84	62.75	62.80	62.76	62.76
Q (W)	259.0	259.1	257.4	256.2	261.1	261.0
LMTD	22.09	22.09	22.33	21.96	22.29	21.97
U (W/m^{2}K)	293.1	293.3	288.2	291.6	292.9	296.9
Efficiency	0.57	0.55	0.52	0.51	0.52	0.50

Table A.32. 18 l/s, 60%, 70^{0}C experiments at 35^{0}C cooling fluid temperature

	Exp187	Exp188	Exp189	Exp190	Exp191	Exp192
Air flow rate (l/s)	18	18	18	18	18	18
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0107	0.0107	0.0107	0.0107	0.0107	0.0107
T1 (^{0}C)	34.9	35.2	35.0	34.9	35.1	34.9
T2 (^{0}C)	42.3	42.3	42.2	42.1	42.2	42.2
Condensate rate (kg/s)	0.000092	0.000093	0.000099	0.000089	0.000090	0.000085
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.56	67.53	67.53	67.54	67.48	67.55
Mixture outlet temperature (°C)	62.19	62.18	62.25	62.25	62.23	62.27
Q (W)	331.2	320.8	324.9	324.7	317.2	324.1
LMTD	25.79	25.61	25.78	25.87	25.69	25.84
U (W/m^{2}K)	321.0	313.1	315.0	313.8	308.6	313.6
Efficiency	0.68	0.71	0.74	0.67	0.69	0.64

Table A.33. 20 l/s, 60%, 70^{0}C experiments at 35^{0}C cooling fluid temperature(repeated experiments)

	Exp193	Exp194	Exp195	Exp196	Exp197	Exp198
Air flow rate (l/s)	20	20	20	20	20	20
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0107	0.0107	0.0107	0.0107	0.0107	0.0107
T1 (^{0}C)	35.15	34.94	34.92	35.12	34.89	34.81
T2 (^{0}C)	42.65	42.52	42.45	42.51	42.46	42.45
Condensate rate (kg/s)	0.000092	0.000101	0.000088	0.000103	0.000091	0.000099
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.73	67.63	67.67	67.62	67.64	67.62
Mixture outlet temperature (°C)	62.51	62.38	62.39	62.34	62.34	62.28
Q (W)	335.6	339.1	336.6	330.7	338.7	341.7
LMTD	25.70	25.74	25.82	25.65	25.78	25.77
U (W/m^{2}K)	326.5	329.3	325.8	322.4	328.5	331.5
Efficiency	0.67	0.73	0.64	0.76	0.65	0.71

Table A.34. 18 l/s, 60%, 70^{0}C experiments at 40^{0}C cooling fluid temperature

	Exp199	Exp200	Exp201	Exp202	Exp203	Exp204
Air flow rate (l/s)	18	18	18	18	18	18
Air humidity (%)	60	60	60	60	60	60
Water flow rate (kg/s)	0.0107	0.0107	0.0107	0.0107	0.0107	0.0107
T1 (^{0}C)	39.90	39.52	39.85	39.82	39.32	39.86
T2 (^{0}C)	45.56	45.43	45.49	45.46	45.27	45.58
Condensate rate (kg/s)	0.000066	0.000072	0.000071	0.000067	0.000077	0.000073
Air temperature (°C)	70	70	70	70	70	70
Mixture inlet temperature (°C)	67.61	67.51	67.53	67.51	67.52	67.49
Mixture outlet temperature (°C)	62.64	62.61	62.63	62.65	62.64	62.64
Q (W)	253.1	264.3	251.9	252.6	265.8	256.1
LMTD	21.97	22.14	22.00	22.02	22.35	21.92
U (W/m^{2}K)	288.0	298.3	286.3	286.8	297.3	292.0
Efficiency	0.64	0.67	0.68	0.64	0.71	0.69