TECHNICAL UNIVERSITY OF
CIVIL
ENGINEERING OF BUCHAREST
Building Services Engineering Faculty
CAMBI Research Center

**SUMMARY
OF THE
DOCTORAL THESIS**

# ADVANCED ENERGY RECOVERY SOLUTIONS FROM THE WASTE WATER FOR THE PROTECTION OF THE ENVIRONMENT

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# 1 GENIRAL INTRODUCTION

The European Union has suggested a strategy to move towards a low-carbon economy by 2050**[1]**. The aim of the Strategy is to reduce carbon emissions by 80 percent by 2050, relative to 1990 levels. The roadmap further notes that the use of energy in buildings is one of the key strips responsible for greenhouse emissions. One of the main factors to achieving this aim is to improve energy efficiency, particularly in houses, which account for around 40 % of total energy requests [2]. Using up A large proportion of energy expenditure as a whole. This consumption is estimated to account for 23 percent of overall consumption in the United Kingdom [3], and 17 percent is recorded in Hong Kong[4]. A large proportion of energy usage is correlated with water heating operations in household energy consumption[5], i.e. washing, water-related appliances, and cooking. 26 percent of local energy usage in the United Kingdom is related to water heating activities[6]. Most of the energy consumed for household operations and/or equipment in heating water is lost[7].

The reduction of energy usage for the purpose of heating water is one of the methods of reducing energy demand by only consumers [8]. Systems focused on both renewable energy [9] and recycled waste energy [10] can be used for this purpose like sewage water[11]. However, using Drain Water Heat Recovery (DWHR) units, the heat transferred by wastewater is more generally retrieved[12]. Other papers, were focused on the particular implementation. such as dishwashers (Hoak et al. [13], Persson [14], Jeon g and Lee[15], Paepe et al. [16], Saker et al. [17], Persson and Roennelid [18], Bengtsson et al. [19][31], Lin et al. [20][25], Hauer and Fischer [21] washing machines (Stamminger[22], Persson [14] and Persson and Roennelid [18], Pakula and Saker et al. [17] and barber shops (Sun et al. [23] or on the evaluation of wastewater sources in an experimental (Ramadan et al. [24]).

When the system is mounted in a primarily horizontal direction, the performance of such DHWR devices safely compromised. Researchers in China demonstrated in an apartment building the efficiency of the horizontal DWHR system for the recovery of energy from shower drains at 5-15% [4]. Similarly, experiments in Ireland on a coiled DWHR device found that when the DWHR device was in a horizontal orientation, an efficiency of 67 percent in the vertical orientation fell to 17 percent [25]. This also rose from 3.7 to 15.1 years, the approximate payback period on the unit. Different experiments have been carried out on horizontal heat exchangers [4, 26]. The performance of such a system was evaluated by Wong et al. [4], proving that it was faint. In response, in order to satisfy the requirement, tried to change the efficacy of this system McNabola and Shields[26]. *All these methods are classical and have been applied to classical heat exchangers but no one of them has been yet applied to a wastewater double heat exchange interface on a wastewater pipe.*

There are several heat transfer improvement strategies for heat exchangers, such as increasing the region of heat transfer, increasing turbulence, reducing the thickness of the boundary layer, creating secondary flow, adjusting the flow rate, and examining temperature gradients[27].

### 1.1 AIMS OF THE THESIS

1. Identifying the possibility of using heat exchangers to recover heat from wastewater;
2. Finding methods to improve the heat transfer between wastewater and cold water;
3. Developing an experimental setup in order to perform measurements of the temperatures, flowrates and velocity profiles to study flow patterns for different geometries;
4. Developing a numerical model in order to perform simulations for different geometries for the heat exchanger;
5. Validation of the numerical model using the experimental results.

## 2 State of the art

### 2.1 Horizontal heat exchanger system

There are many studies conducted to improve the effectiveness recover of heat transfer of domestic water in the horizontal since this method is economically inexpensive, and does not require a large area and can be installed in the first floor through which thermal energy can be recovered of all the wastewater.

**Proposed Pochwat et al. [6]** in his study a new design to improve the efficiency of heat transfer in the horizontal and in counterflow. The experiment is consist of the greywater pipe (PVC) with a diameter of 40 mm and the copper water pipe with a diameter 12.7 mm passing through it. And the copper water pipe was positioned at the bottom of the greywater pipe to improve heat exchange. And concluded it is theoretically possible to design the DWHR system to operate with a satisfactory level of efficiency in a horizontal. The results also show that, depending on a variety of external factors, such a system can be economically viable. It has been shown that it will considerably scale back energy usage and dioxide carbon emissions by implementing this technology at the national level. The efficacy of the prototype was found to be 23 percent. The effect of raising the drain water temperature to 65 $^{o}$c and lowering the drain water flow rate to 6 L / min was found to slightly increase the efficiency above this value. The hot water flow rate was found to be an essential determinant of system performance, with flow rates above 10 l / min being significantly lower regarding efficiency than flow rates below 10 l / min in general terms.

**Wong et al. [8]** Investigated his study was heat the recovery of the shower at the residential building (high rise in Hong Kong). The primary objective of its experiment was to estimate the minimum heat transfer area needed for the duty in question, as it regulates the overall heat exchanger outlay. The setup of the experiment was to compute the lack of the effectiveness E of the heat exchange singles pass (counter flow) in horizontal, the heat exchanger consists of the cold water pipe (PVC)with long 1 m, diameter 0.1 with a hot water pipe (copper) with 40 mm diameter passing through it. The copper pipe of hot water that simulates a slope drainage pipe is partly filled with hot water. It was noted that gravity water flows can be defined by simple fluid flow principles in partially filled slope drainage pipes. Using the effectiveness-number of transfer units (ε-NTU) method, the thermal energy exchange is measured. The results show that 4-15 percent shower water heater for a drainage pipe of 50 mm diameter can be recovered through a 1.5 m long single-pass counter-flow heat exchanger. In hot and humid climates, waste heat recovery from shower drains in high-rise residential buildings is difficult. Good heat exchanger designs with a justified payback period are required, apart from space limitations for the installations.

**Kamil et al.[28]** their analysis was a comparison of two prototype efficiency-based recapture units of near-horizontal drain water heat. In connection with the test of the effectiveness of this unit, this study aimed to present the finding of the project. In this analysis, there are two parts of the experiment: a simple horizontal heat exchanger (HE-0) and a new heat exchanger (HE-1). A significantly horizontally focused body made of plastic to move greywater is part of the heat exchanger HE-0. There is a copper conduit positioned parallel to the lower inner portion of the body to move the water to be heated in the opposite direction to wastewater. Via the conduit walls, the heat stored in the latter is transferred. Such a system design eliminates all interaction between the two flowing media. A downside of the solution is the efficacy of a relatively low heat exchanger that is verified by the study mentioned in this experiment. The operating concept of the current HE-1 brand heat exchanger is comparable. The heat exchange efficiency attainable in this case, however, is significantly higher. The effect was achieved by inserting baffles into the device's body, resulting in growing the time in the DWHR system for the water to remain. It was concluded through this study the heat exchanger created is especially intended for residential buildings with low consumption of shower water. In certain situations, by separating the streams of both media into two or more heat exchangers, there is a possibility to improve the efficacy of the heat greywater heat recovery system.

# 3 Measurement techniques and tools used

## 3.1 Measuring water temperature

### 3.1.1 Thermocouples

The thermocouple used in this study is k type 190-2 from ALMEMO to measure the temperature of the water and it is the most common type. It is possible to change any sensor, i.e. the sensor's correction values can be stored in the connector and all these connectors are used to connect the sensor to the data logger ALMEMO.

### 3.1.2 Data logger ALMEMO

In the CAMBI Laboratory, there are ALMEMO devices used in Exp.1 ALMEMO 2690-8 with 4 connectivity ports, and the Exp. 2, 3 and 4, use the ALMEMON 710 with 10 connectivity ports. These devices are used to read and record the temperature of greywater and fresh cold water used in this study.

## 3.2 Measurement of flow velocity

### 3.2.1 Ultrasonic Flow Meter for Liquids (PT900 Portable)

The PT900 is a portable transmitter for measuring liquid products. It's used to measure the velocity of the water flow in the experiments. Using a new electronic platform and an industrial design simplified to make it easy to install and use. The system includes a tablet running Android [29].

We used it to measure the velocity of water in the pipes in this study, this device is existing in the CAMBI laboratory in the College of Service Engineering.

### 3.2.2 Measurement Technology of Particle Image Velocimetry (PIV)

The measurement process for greywater molecules motion is done around the copper tube for cold water, as the laser is prompt at the top of the copper tube in the middle, as well as laser between these two copper tube, and the camera is next to these pipes to take the images for Molecules motion, and During those experiments recording the readings of flow velocity and temperature

The PIV technique enables the specific conception, of turbulent flows and the quantitative determination of the speed assignment in the analysed field [30-32].

The camera used to obtain the images is flowsense EO NIK-C, with a Nikon lens with a focal length of 50 mm and an aperture of 1:1.2. The FlowSense EO camera can capture pictures at 4.7 frames per second with a maximum resolution of 6576 × 4384 pixels. However, the fast FlowSense EO VGA can record pictures at up to 260 frames per second. Furthermore, the new FlowSense EO 4M-32 allows you to capture double frame pictures at a rate of 15 Hz, which is comparable to the repetition rate of many high-power lasers. Pixel sizes range from 3.45 gm to 9.0 gm. Images stored in the camera's internal memory are transferred at the end of each computer acquisition. To illuminate the tracer particles in the flux (the particles are spheres with a diameter of 10 µm) a Nano power infrared laser was used, with a power of 4W producing a wavelength of 795 nm[33]

# 4 Experimental setup

## 4.1 First experimental campaign

The experimental unit was built for the effectiveness assessment of the heat transfer rate with five cold water velocities as shown in figure 4.1. The experiment unit is consists of the bathtub which connected with a PVC pipe to drain greywater and the copper cold water pipe passing through the PVC pipe at the bottom and is equipped with a valve to control the flow velocity of cold water, the source of the cold water from the laboratory water network. A schematic diagram of the experiment unit is shown in figure 4.2. The resource of hot water from the heater installed in the laboratory.

The experiment unit works based on the heat exchange between hot greywater and cold water. The hot water tap is turned on to the maximum and pours water into the bathtub (the flow rate is constant). The temperature rate of the greywater and cold water is measured by thermocouples Type-k with the data logger (ALMEMO) device. The cold water flow rate is measured by the Ultrasonic Flow Meter PT900, Which is installed on the copper cold water pipe. When changing the velocities of cold water from (q1 to q5) measures the temperature to find out the effect on the effectiveness, and the measurement period is 10 minutes for each velocity.


*Figure 4-1. Experiment unit of Exp. 1.*

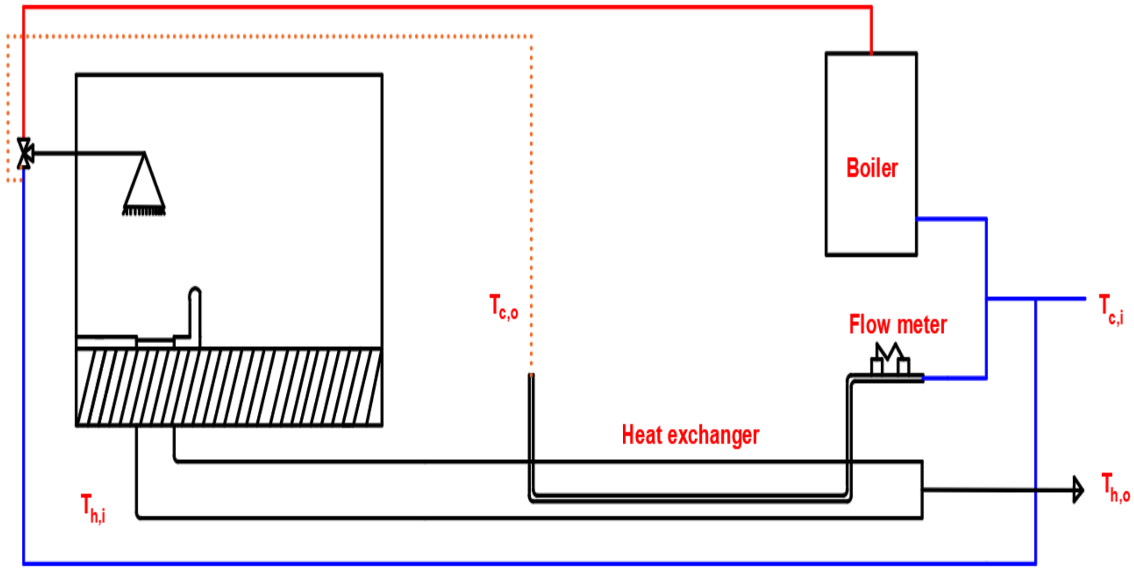



*Figure 4-2. The schematic diagram for the experimental unit of Exp. 1.*

### 4.1.1 Single Heat exchanger

The heat exchanger is the copper cold water pipe with diameter 10 mm, 1000 mm length and 0.7mm thickness, passing through the PVC pipe of greywater with diameter 40 mm in horizontal, and counter flow for transfer of the heat from hot greywater to cold water as shown in (figure 4.3). Simplified diagram of heat exchanger.


*Figure 4-3. The heat exchanger for the experimental unit of Exp.1.*

## 4.2 Second experimental campaign

The experimental unit was built for development and effectiveness assessment of the heat transfer rate for three velocities of greywater with five velocities of cold water, distribution the temperature along two copper cold water pipes as shown in figure 4.4. A schematic diagram of the experiment unit is shown in figure 4.5.

The experiment unit consists of the Plexiglas greywater pipe and two copper cold water pipes passing through the Plexiglas greywater pipe at the bottom and is equipped with a valve to control the flow velocity of cold water, the source of the cold water from the laboratory water network, two tanks of greywater, a pump with three velocities used to transport the greywater from the tank (1) the tank (2), Through a copper pipe connected between them with a diameter of 40 mm and three heaters to heating the greywater (one heater in the tank 1 and two heaters in the tank 2). The greywater level rises in the tank (2) and exits into the Plexiglas greywater pipe and then it runs to the tank (1) by the slope.

The experiment unit works based on the heat exchange between hot greywater and cold water. Determine the required velocity of cold water through the valve, such as the first velocity of cold water q1 with the first velocity of greywater Q1, the duration of the measurement is 10 minutes, then remains the first velocity q1 of cold water, and change the velocity of greywater to the second velocity Q2 and wait for five minutes, and then start the second measurement and for 10 minute Others, also doing the same process to change to the third velocity of greywater Q3, after the completion of this three-velocities changes the velocity of cold water to the second q2, third velocity q3, q4, and q5, conduct the same process with the first velocity q1. During different flux velocities, the temperature of greywater and cold water is calculated to determine the effectiveness of heat transfer rate.

The temperature rate of the greywater and cold water is measured by thermocouples Type-k with the data logger (ALMEMO 710) device. The flow rate of the cold water and greywater is measured by the Ultrasonic Flow Meter PT900, Which is installed on the copper cold water pipe and the copper pipe connected between tank 1 and tank 2.


*Figure 4-4. Experimental unit Exp. 2.*

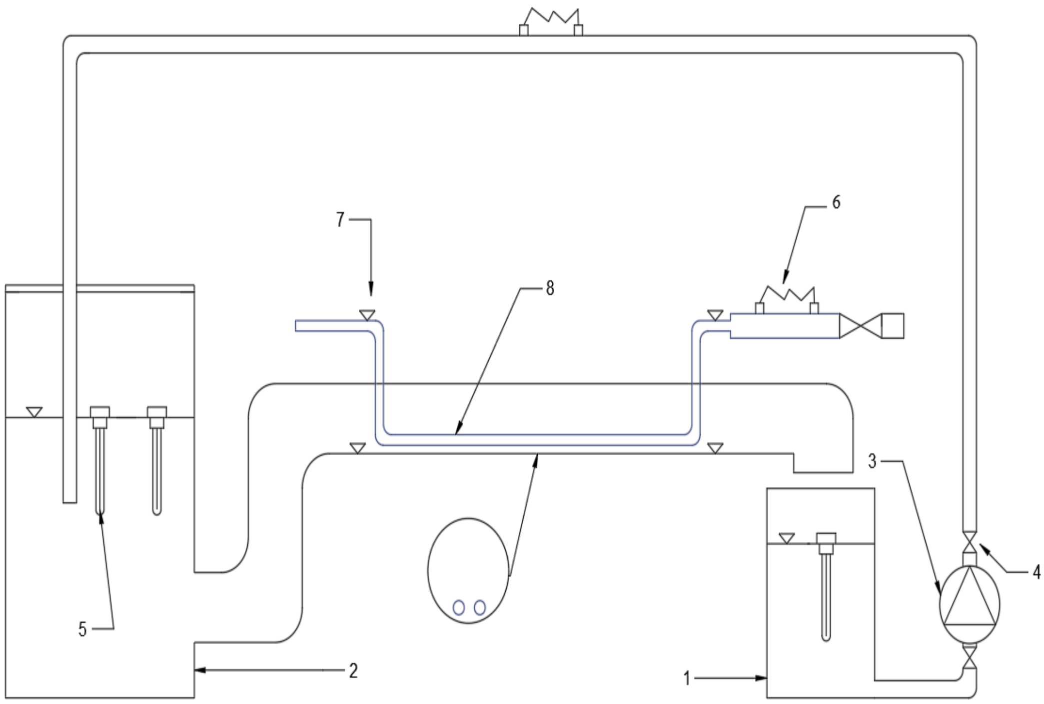
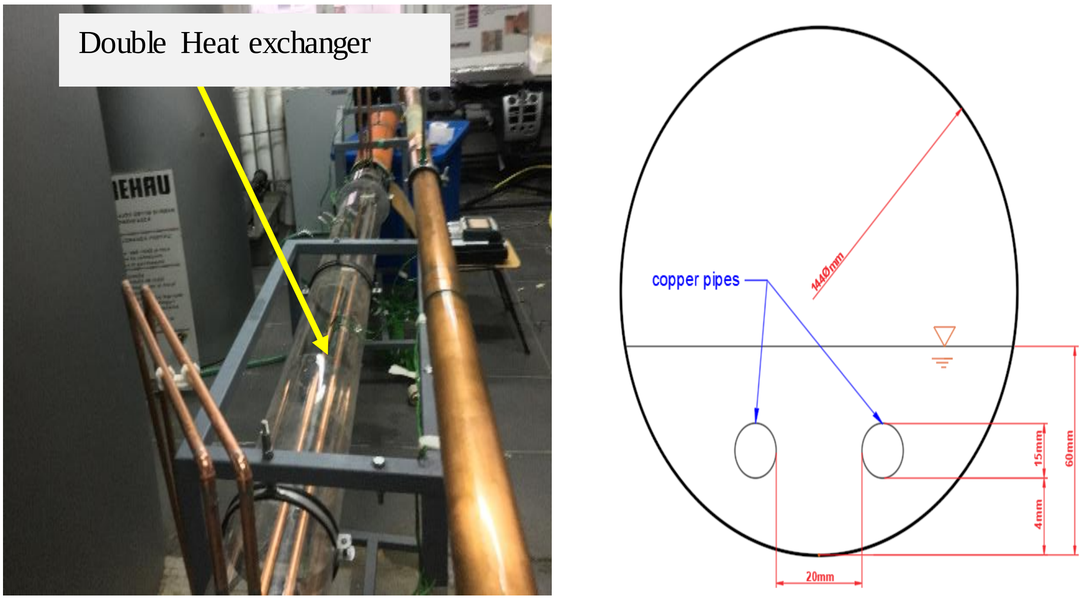



*Figure 4-5. Schematic diagram of the experiment unit of Exp. 2: (1- first tank, 2- second tank, 3-greywater pump, 4- valve, 5- heater, 6- ultrasonic flowmeter, 7- thermocouples, 8- double copper pipe).*

### 4.2.1 Double Heat exchanger

The heat exchanger is two copper cold water pipes with an outer diameter of 15 mm and 1890 mm length 0.7mm thickness, passing through a Plexiglas greywater pipe with an outer diameter 150 mm and 3mm thickness in horizontal, and counter flow for transfer of the heat from hot greywater to cold water (see figure 4.6).




*(b)*

*Figure 4-6. Double heat exchanger for the experimental unit Exp. 2: a) double heat exchanger,* b) cross section for pipes (heat exchanger).

## 4.3 Third experimental campaign

The experimental unit was built for development and effectiveness assessment of the heat transfer rate for three velocities of greywater with three velocities of cold water, distribution of the temperature along two copper cold water pipes, comparison with the experiment in Exp. 4 (with twist tape), as well as the effect of changes of the greywater temperature on the effectiveness of the heat transfer rate ((only in this Exp.)).

This experiment unit is the same as the previous Exp. 2, but its difference in the distances between the copper cold water pipes, which are increasing in this Exp., and the level of these copper pipes at the bottom of the greywater pipe is higher, to avoid contact between the twist tape of Exp. 4 with the bottom of greywater pipe, and for comparison between the pipe without tape and pipe with a tape. Schematic diagram of the cross section for pipes (see figure 4-7), this experiment is the same methodology for the experiment of the Exp. 2.

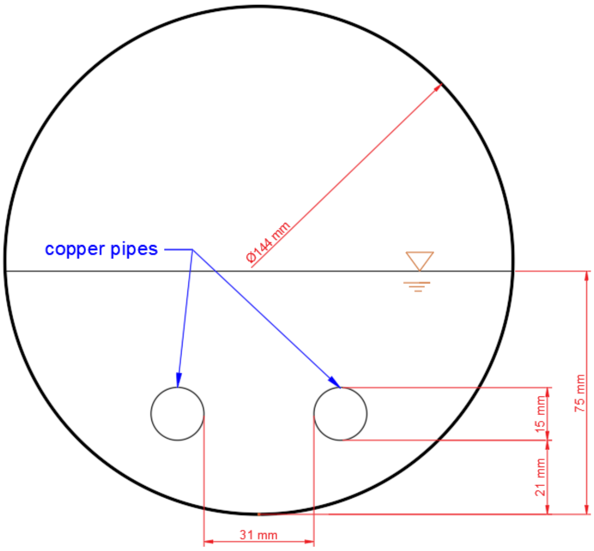
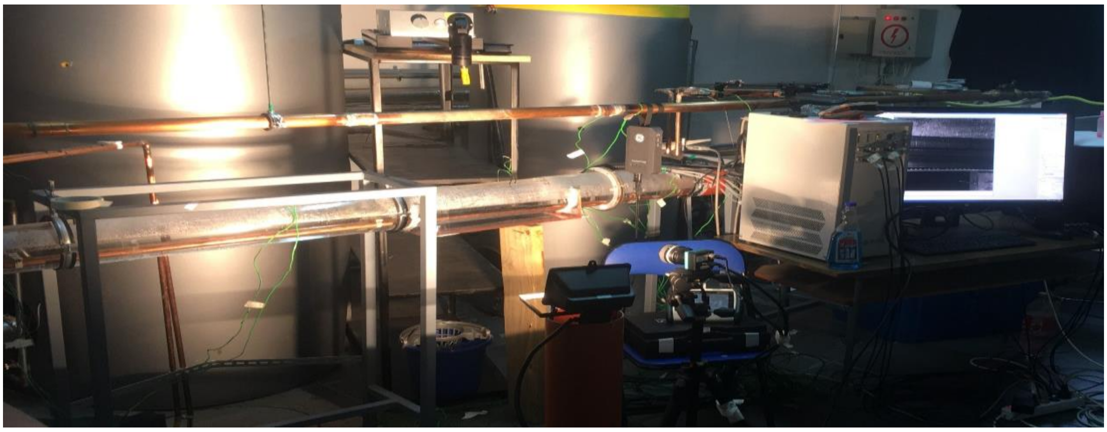



*Figure 4-7. Schematic diagram for the new distance between of the copper cold water pipes and its location in the greywater pipe.*

Figure (4-8) is shown the installation of the PIV technology, PIV technology was used to measure the velocities of greywater around the copper cold water pipe.

**In this case, two experiments were conducted**: the first; when the laser is directed towards the copper cold water pipe centre (on pipe), the second; when the laser is directed between two copper tubes of the cold water. We measured the effect of velocities of the cold water and greywater on heat transfer rate (effectiveness), as well as the PIV technology.


**(a)**



**(b)**

*Figure 4-8. The measurement process for greywater molecules velocity by PIV technology: a) When the laser is directed towards the copper cold water pipe (on the pipe and between pipes), b) the photo when conducting the calibration for PIV technique before measurement*.

## 4.4 Forth experimental campaign

This experiment is the same as the experiment in Exp.3, but; the difference is to adds the twist tape around the copper cold water pipes, in order to improve the effectiveness of the heat transfer rate, and then compare it with the smooth pipe (without twist tape) in Exp.3.

The PIV technology has been measured the same in Exp.3, but the difference is to add another measurement of PIV technology when the camera was near pipes because the motion of particles in greywater around the copper cold water pipes is not clear at the first time so the camera moved to near the tubes and performed the second measurement.

### PROCEDURE FOR FORMING HELICAL SCREW TAPES

After completion of steps for the calculation of the annular-shaped (copper pieces):

1- Projection of the planning on the copper plate with 0.4 mm thickness as shown in figure (4-9).

2- This copper plate is cut to pieces by using manual scissors as shown in figure 4-10.

3- Locate these pieces on the tube, and depending on this tube diameter and twist length and (see figure 4-11).

4- Welding these pieces with each other and with the copper cold water pipe by using the Solder Wire /Tube Tin Lead Rosin Core as shown in figure (4-12).

5- These pipes are pigmented by black colour in order to conduct the measurement technique PIV as shown in figure 4-13.

6-These pipes are connected to the experiment instead of the smooth pipes. The schematic diagram for the distance between the copper cold water pipes with twist tape and its location in the greywater pipe see figure 4-14. And all these processes are made in the Laboratory

Figure 4-9.Projection of the planning on the copper plate.

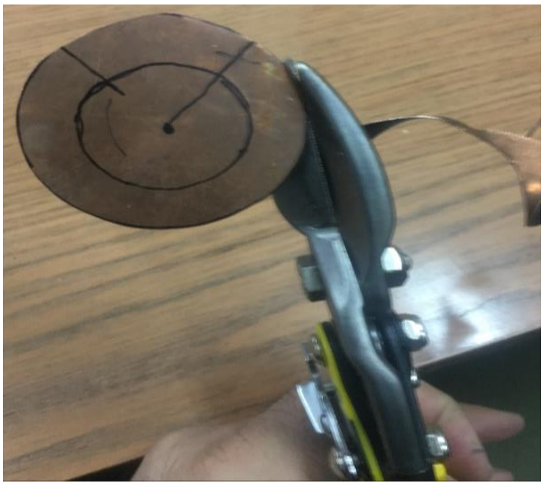


*Figure 4-10.cut of the copper plate to pieces.*

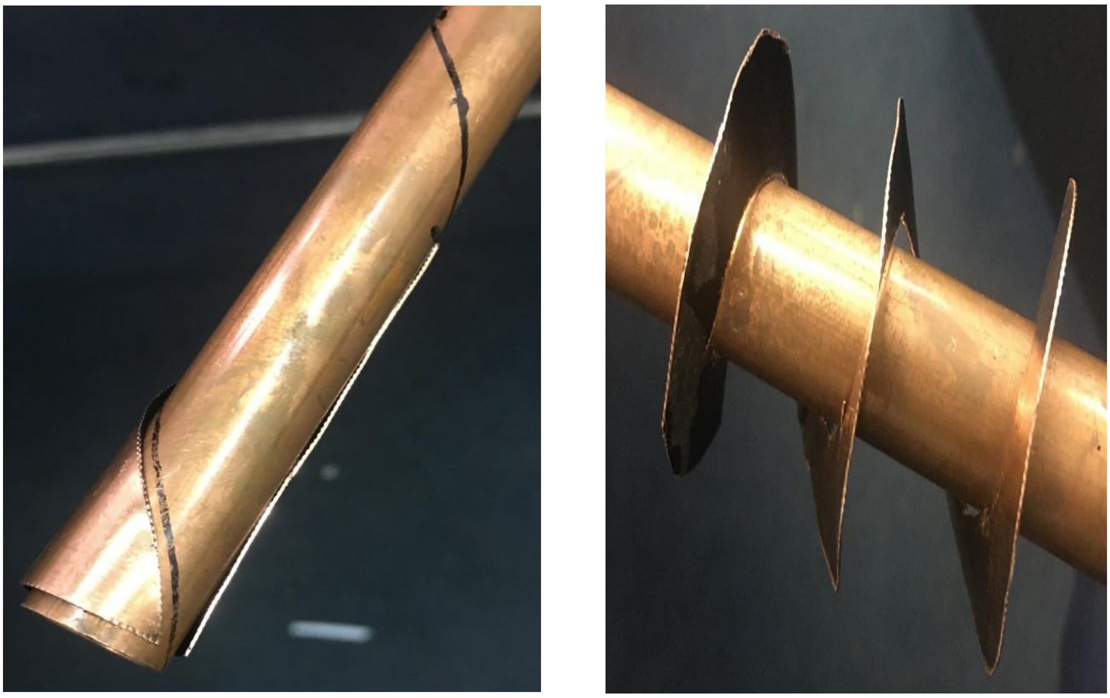
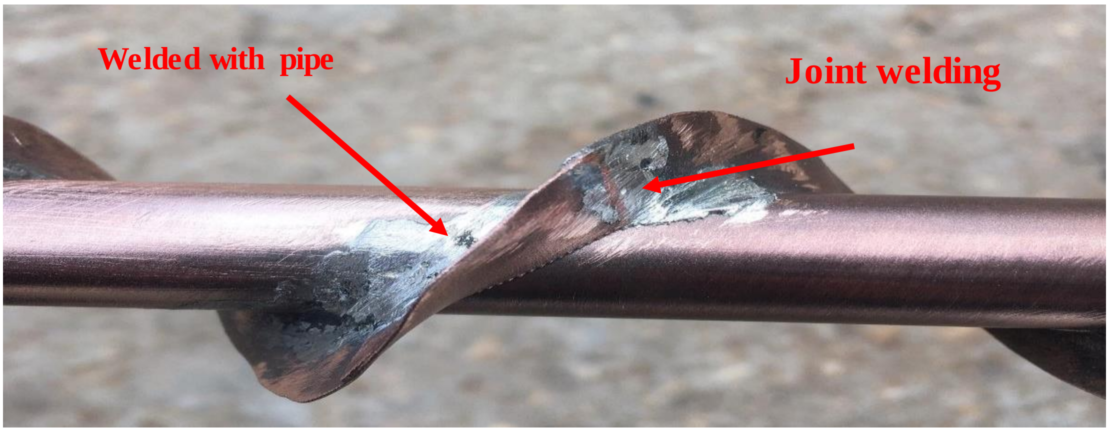


*Figure 4-11. Locate the copper pieces on the pipe.*

*(a)*




b)

Figure 4-12. Welding process for the helical twist tape, a) Carry out the welding process in the workshop lab (CAMBI), b) Welding these pieces with each other and with the copper cold water pipe.

Figure 4-13. Dye these tubes in black.

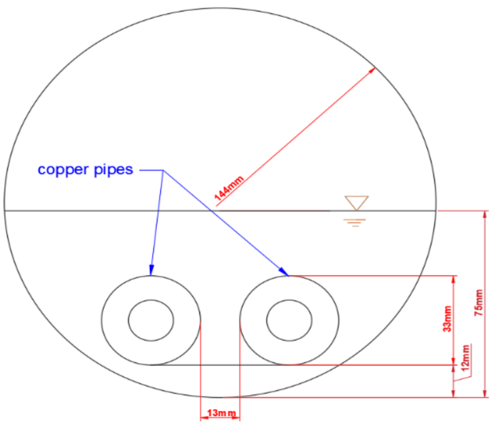


Figure 4-14. The schematic diagram for the distance between the copper cold water pipes with twist tape.

# 5 Experimental results

## 5.1 First experimental campaign

The results obtained from Exp.1 the temperature of cold water and greywater at the inlet and outlet, and five velocities of cold water was range 0.28 to 1.99m/s. As well as the compare effectiveness with cold water velocity changes to find out its impact, the effectiveness was 13% to 24% with the maximum velocity of cold water to minimum velocity respectively see figure 5-1.

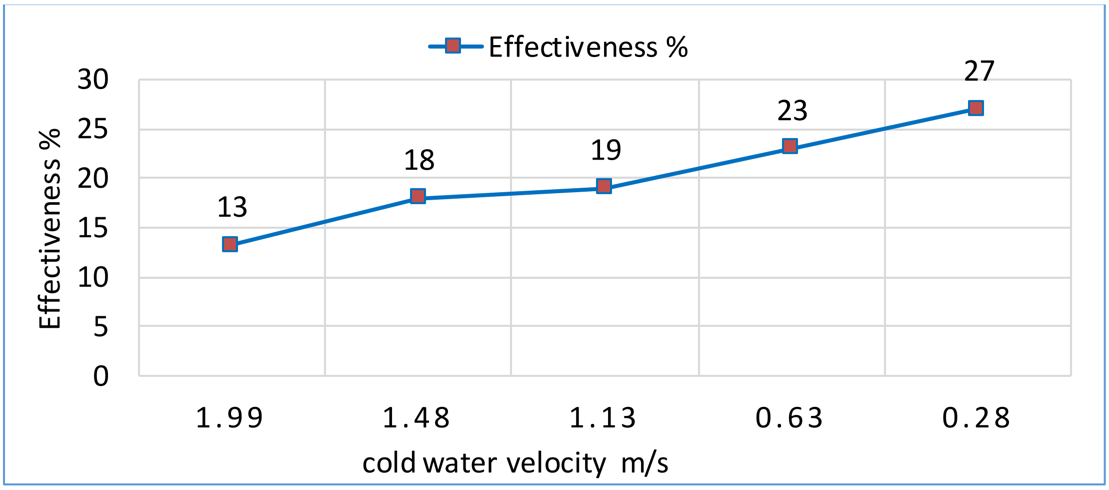



Figure 5-1.The relevance between the effectiveness and the flow velocity of the cold water in the Exp.1.

## 5.2 Second experimental campaign

The results of Exp.2, the temperature of the cold water and greywater at the inlet, with five velocities of the cold water, three velocities of greywater, are 0.28, 0.27, and 0.23 m /s, as well as temperatures distribution along the cold water tube (double heat exchanger), is increasing towards the outlet as shown figures 5-2, 3-48, the highest velocity of cold water was 0.97 m /s with the lowest effectiveness 24%, lowest velocity 0.26 m /s, with the highest effectiveness was 44%, The difference in the velocity of greywater Q2, Q1 and Q3 was not an important influence on the effectiveness of heat transfer.

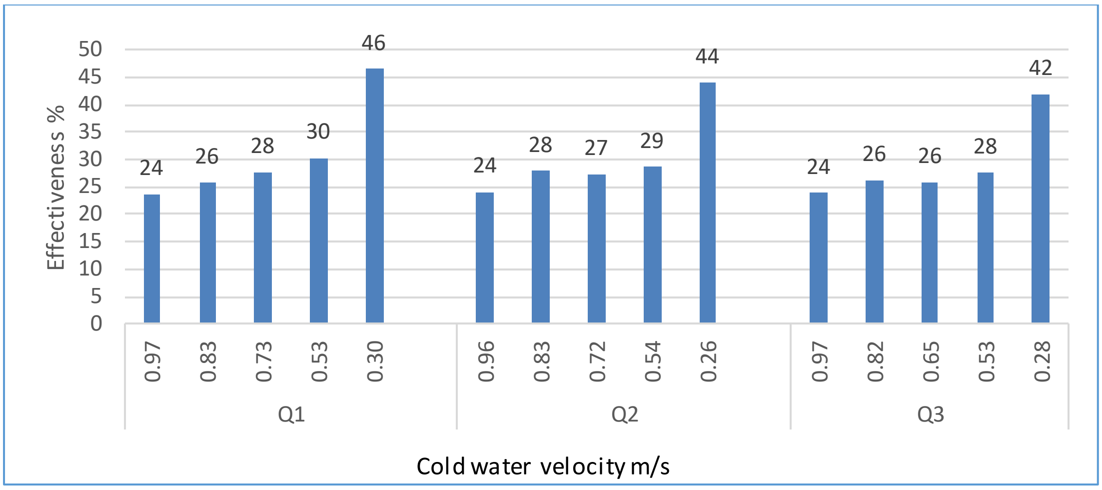



Figure 5-2.The relationship between effectiveness and cold water velocities for the three velocities of greywater.

### 5.3 Third experimental campaign

The results of the third Exp. for smooth pipes, the temperature of the cold water and greywater at the inlet and outlet, with three velocities of cold water, when the laser is directed between the tubes of cold water through the use of PIV techniques. three velocities of greywater, are 0.17, 0.16, and 0.14 m /s, as well as temperatures distribution along the cold-water tube (double heat exchanger), is increasing towards the outlet, The highest velocity of cold water was 0.71 m / s with the lowest effectiveness 26%, lowest velocity 0.46m /s, with the highest effectiveness was 31%, The difference in the velocity of greywater Q2, Q1and Q3 was not an important influence on the effectiveness of heat transfer see figure 5-3.

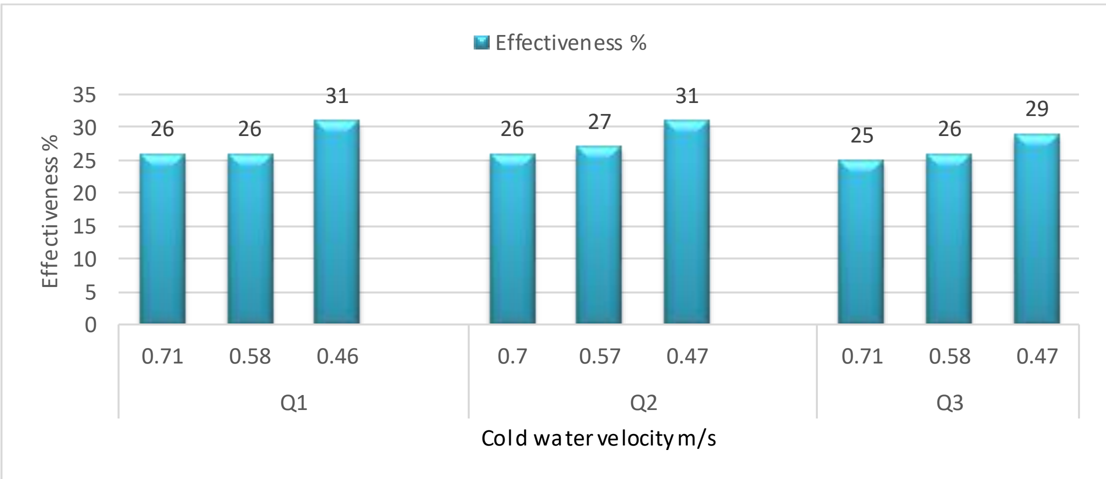



Figure 5-3. The relationship between effectiveness and cold water velocities for the three velocities of greywater, when the laser is directed between the tubes.

### 5.3.1 The effect of greywater temperature change on the effectiveness

Results of the effect of greywater temperature change on the effectiveness of heat transmission rate, with fixed parameters of greywater velocity (0.16 m /s), cold water velocity was 0.41 m /s, and there were four different temperatures of grey water (43-38-33-28 C).

Through these results, we note that the temperature change has not affected the effectiveness when increasing the temperature of greywater leads to increased cold water temperature at the outlet To,c, when decrease leads to reduce the cold water temperature at the outlet To,c, and therefore the effectiveness is not affected see figure (5-4), but possible It increases or decreases when an increase or decrease of cold water temperature inlet. This experiment has been made in a warm atmosphere and the cold water temperature is high compared to the previous experiment, which has increased the effectiveness.

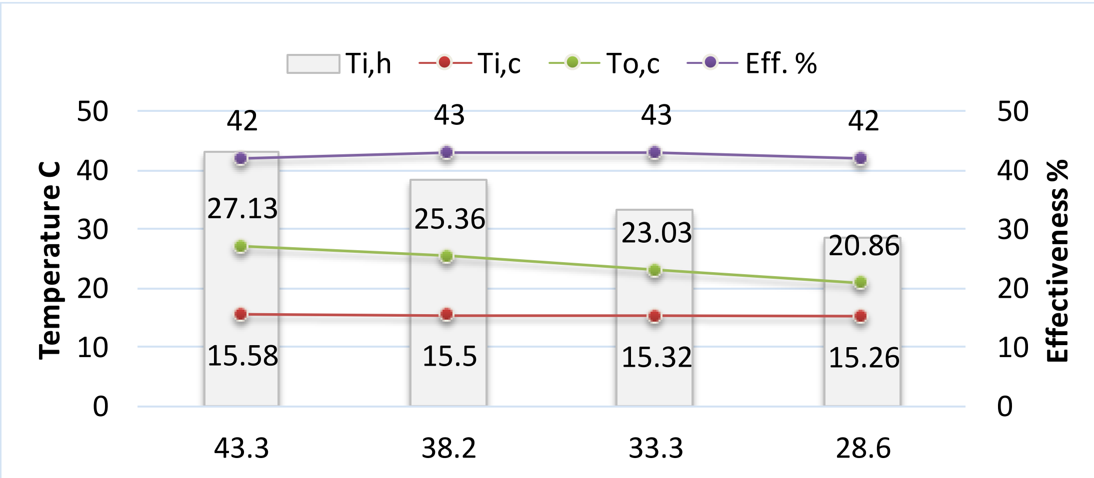



Figure 5-4. The effect of greywater temperature change on the effectiveness.

## 5.4 Forth experimental campaign

The results of the fourth Exp. Using twist tape (helical), when the laser is directed between the tubes of cold water through the use of PIV techniques. the temperature of the cold water and greywater at the inlet, with three velocities of cold water, three velocities of greywater, are 0.17, 0.16, and 0.14 m /s, as well as temperatures distribution along the cold-water tube (heat exchanger), is increasing towards the outlet, The highest velocity of cold water was 0.71 m /s with the lowest effectiveness of 32%, the lowest velocity was 0.46m /s, with the highest effectiveness was 48%, The difference in the velocity of greywater Q2, Q1and Q3 was not an important influence on the effectiveness of heat transfer see figure 5-5.

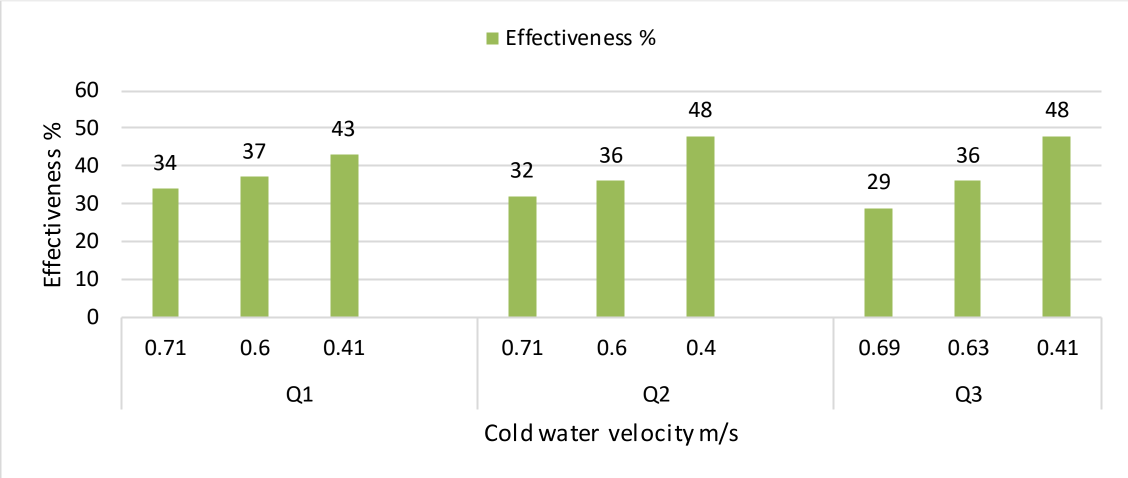
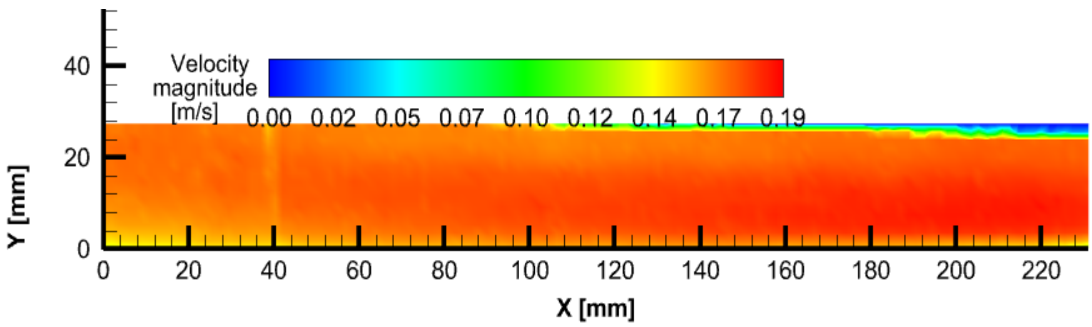



Figure 5-5. The relationship between effectiveness and cold water velocities for the three velocities of greywater, with using the twist tape (helical), when the laser is directed between the tubes.

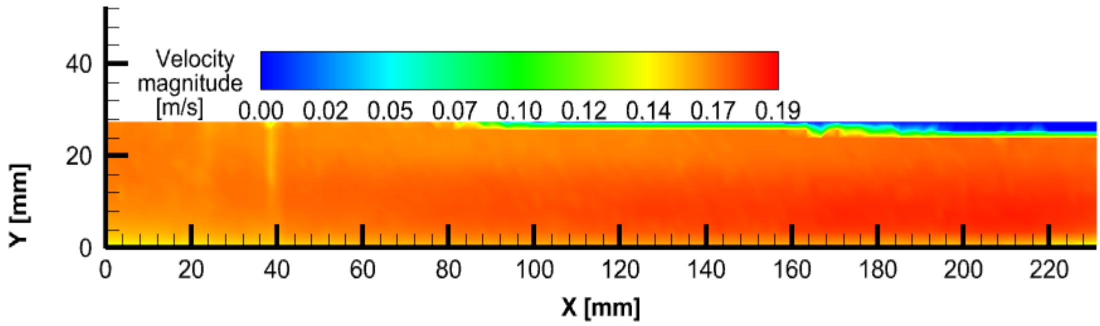
### 5.5 PIV results

This part of the manuscript has presented the result obtained by using the PIV system.

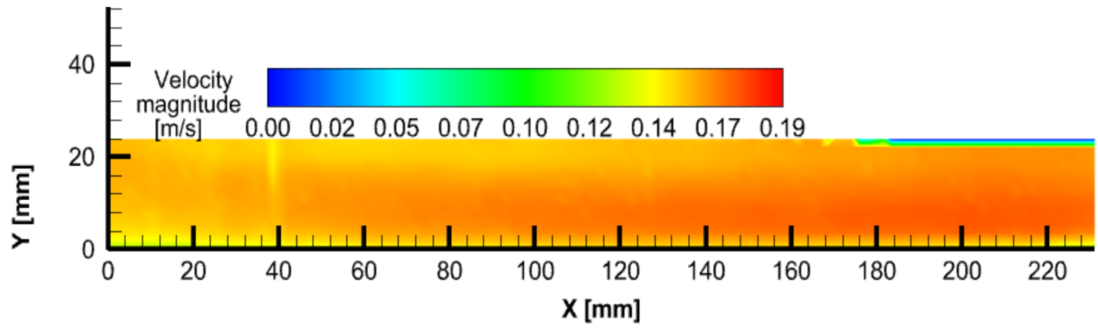
In figure (5-6) are presented the velocity distribution maps obtained on the center of smooth copper pipe. The level of the free surface decreases with a centimetre in the case for the Q3 (fig 5-6 c), comparing with the other cases. Also, the color map shows that the velocities are lower for this case. Between Q1 and Q2 the difference of color map is very insignificant, however, the free surface is larger for Q2, comparing with Q1, due to the lower flow rate.




a)



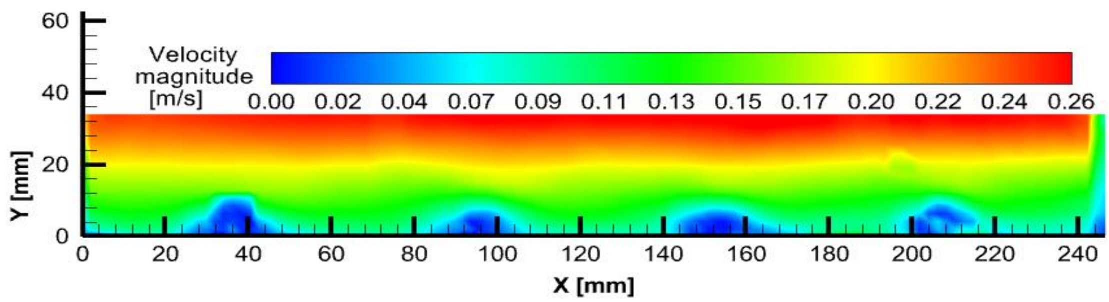

b)



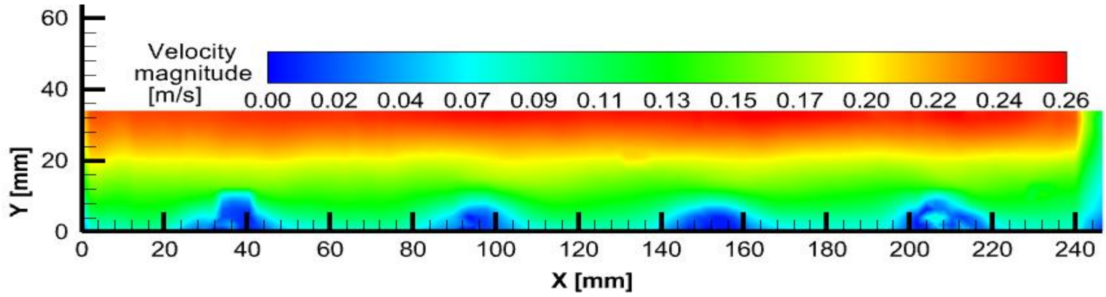

c)

*Figure 5-6 Velocity distribution maps recorded on the copper smooth pipe for a) Q1, b) Q2, c) Q3.*

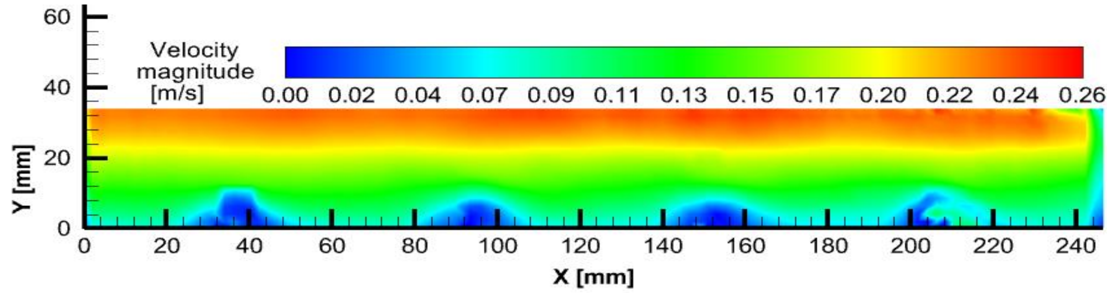
In comparison with the cases with smooth pipes, the case with twist tape (helical screw tape) provides a very non-uniform velocity distribution, the higher velocity being recorded her to the top free surface, while a lower velocity is achieved in the region of the wings (twist tape). The blue heights from the bottom of the figures represent the geometry of the wings. We observe the velocity will decrease on the helical pipes especially in the surrounding area of copper pipelines, the lowest velocity at the Q3 compare to the Q2, Q1 as shown in figure 5-7.




a)




b)




c)

*Figure 5-7.Velocity distribution maps recorded on the copper pipe with helical screw tape for a) Q1, b) Q2, c) Q3.*

Figures (5-8) are represented the vector map distribution, one important remark is regarding the vortices formed behind the wings. In the upper half of the map, the Velocity on the x-axis is dominant, so the majority of these vectors are directed to the outlet. Decreasing, the other two velocity component has a greater influence, leading to stagnation areas.

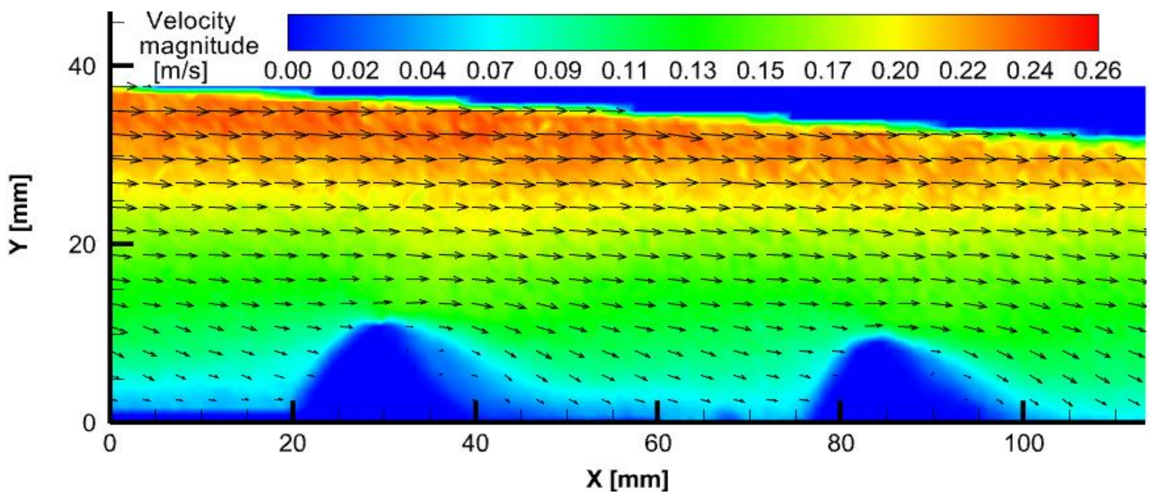
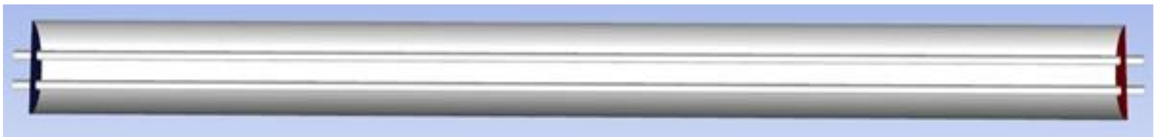


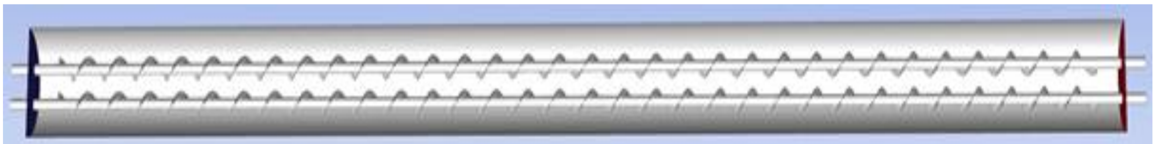

*Figure 5-8. Focused velocity distribution map and vector distribution on the copper pipe with helical screw tape for Q2 of the greywater with q2 of the cold water.*

## 6 Numerical model

The geometries were created in SolidWorks and after that were imported in DesignModeler under Ansys Workbench 19.2 software. In figure 6-1a regular geometry can be seen and in figure 6-1b is presented the novel helicoidal geometry. At this stage, the geometry was prepared for the numerical simulation.



a)



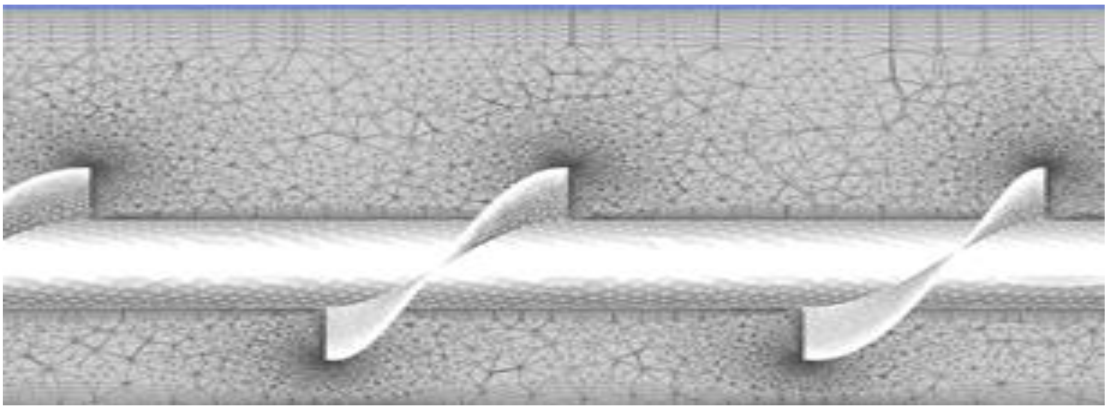
b)

*Figure 6-1. The geometries a) A regular geometry for heat exchanger, b) The novel helicoidal geometry for the heat exchanger.*

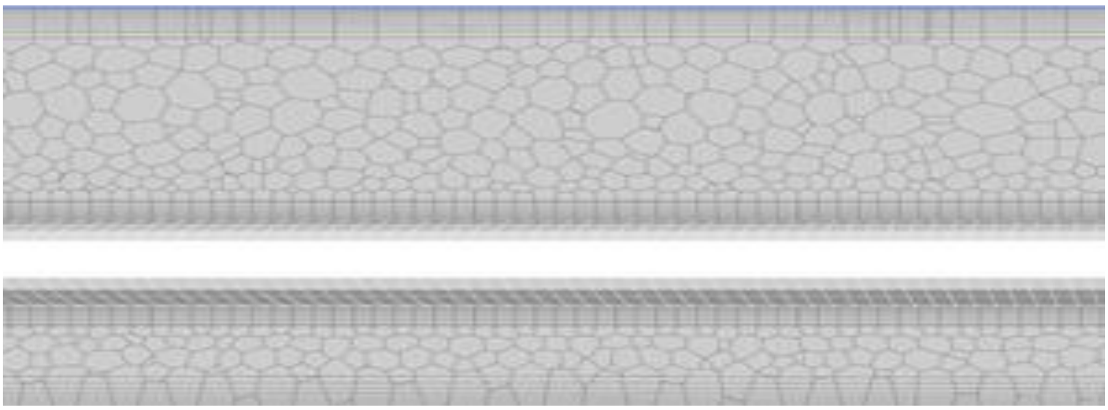
The numerical grid was created for both studied cases in Ansys meshing. Given the fact that the helicoidal geometry is very complex mainly due to the very low thickness of the helicoidal fin (0.4mm) the number of the elements necessary for the numerical simulation was 102 million elements (see figure 6-2a). A mesh independence test was carried out for this geometry (60, 102, 122 million tetrahedral cells). The main difficulty in creating the mesh was related, as it was stated earlier due to the very low thickness of the helicoidal fin. Because the helicoidal fin is causing the disturbance in the flow, it was needed to create a very good mesh around the sharp edge of the fin. Also, a boundary layer of eight cells was created on all the walls in the studied geometry. Due to the long geometry this caused the increased number of cells. We created more meshes with a low number of cells but there were not suitable for the numerical simulation.

The numerical grid for the regular geometry was much simpler to be generated because it does not have any complication. Due to the simplicity of the geometry, was even possible to create a polyhedral mesh in this case (see figure 6-2b). In this case, was also performed a grid independence test which revealed that the numerical grid of 2.66

million polyhedral cells was appropriate for this case (among 1.2, 1.8, 2.66, 3.8 million polyhedral cells). Also, a boundary layer of eight cells was created on all the walls in the studied geometry.



a)

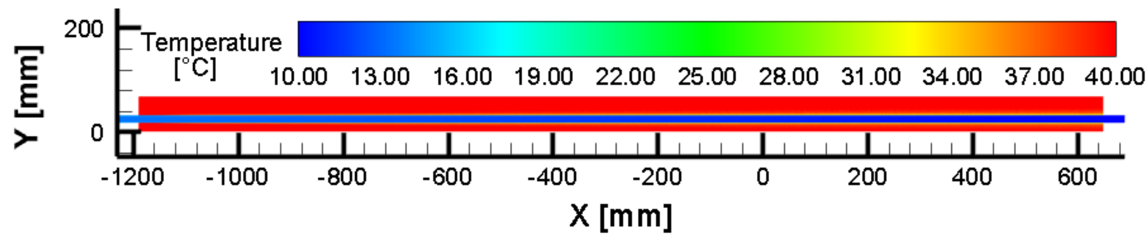


b)

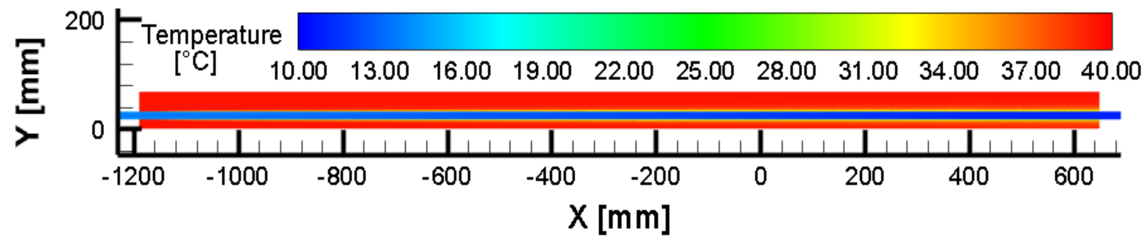
*Figure 6-2. the grid details; a) Numerical grid details for the helicoidal case, b) Numerical grid details for the regular case.*

The numerical simulations were performed in Ansys Fluent 19.2. The turbulence model used for the numerical simulation was SST k-ω due to the high capacity of this model to accurately simulate the flow both in the boundary layer and in the far field [34]. The y+ number had values under 5 on all the wall surfaces from the studied domain which is considered acceptable when using the SST k-ω turbulence model[35].

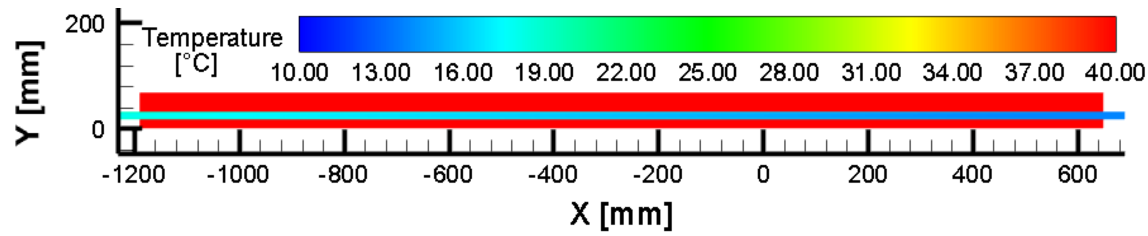
The temperature distribution achieved on copper smooth pipe and along the numerical model is shown in this figure (6-3), the temperature is lowest at the inlet and decreases at the outlet, the cold water temperature increases at the outlet, due to heat recovery (heat transfer from hot grey water to cold water).



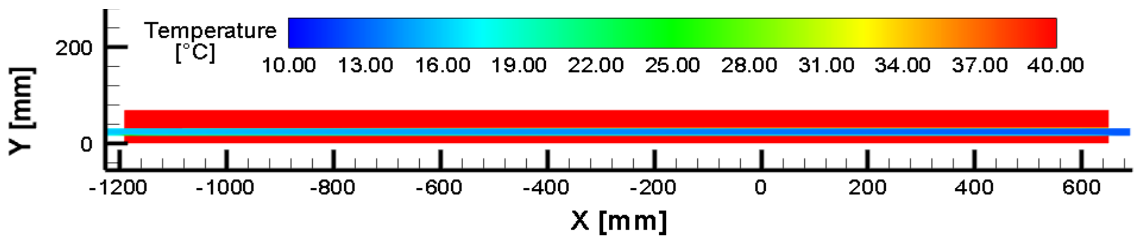

a)




b)




c)




d)

Figure 6-3. The temperature distribution on the copper smooth pipe and along the numerical model for a) Q1 when the laser directed between copper pipes, b) Q3 when the laser directed between copper pipes. c) Q1 When the laser directed on the pipe, d) Q3 When the laser directed on the pipe.

The temperature distribution achieved on helical screw tape copper pipe and along the numerical model is shown in this figure (6-4), the temperature is highest at the inlet and decreases at the outlet, the cold water temperature increases at the outlet, due to heat recovery (heat transfer from hot gray water to cold water).

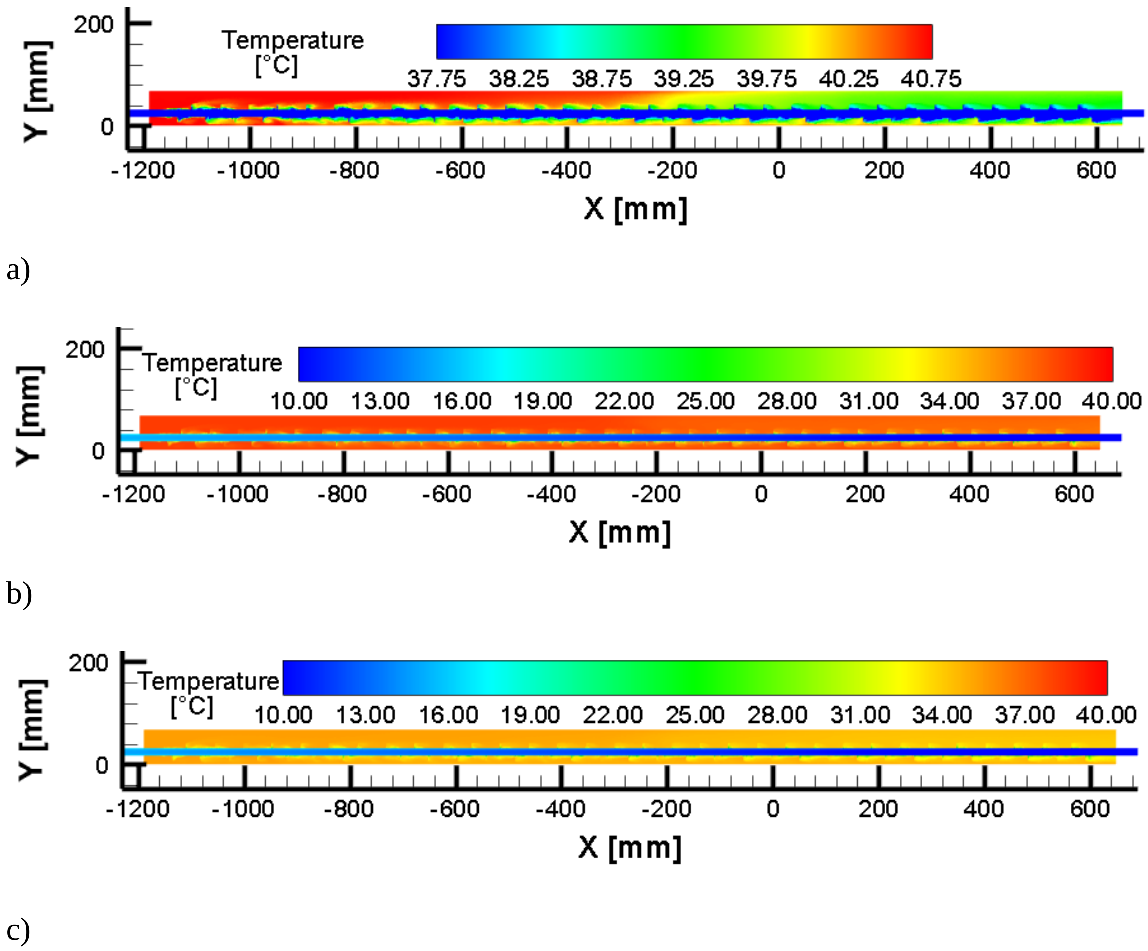



Figure 6-4. The temperature distribution on the helical screw tape copper pipe and along the numerical model for a) Q1 when the laser directed between copper pipes, b) Q3 when the laser directed between copper pipes. c) Q1 When the laser directed on the pipe, d) Q3 When the laser directed on the pipe.

## 7 Conclusions

Through the first Exp. of the experiment, we conclude that the change in cold water velocity affects the efficiency of the heat transfer rate, where the maximum velocity was 1.99 m /s with the lowest effectiveness of 13%, and the minimum velocity was 0.28 m /s with the highest effectiveness of 27%. Therefore, when the cold water velocity decreases lead to increased heat transfer efficiency (effectiveness).

Distribution of the temperature along the cold water tube (heat exchanger) is increasing towards the outlet, with all cold water velocities. These results indicate that the effectiveness of heat recovery is increasing whenever the length of the tube is increasing (Exp. 2, 3, and 4).

The change in cold water velocity affects the efficiency of the heat transfer rate, where the maximum velocity gives the lowest effectiveness, and the minimum velocity gives the highest effectiveness. Therefore, when the cold water velocity decreases lead to increased heat transfer efficiency (effectiveness). (In all Experiments).

The difference in the velocity of greywater, Q2, Q1, and Q3 was not an important influence on the effectiveness of heat transfer, the reason for this apparently is the simple difference in inflow velocity.

There is a simple difference in the velocity of cold water, the main reason for this is the oscillation of cold water flow, which are linked with a network of the laboratory building, where when using water elsewhere as the use of water cycle, that leads to reduce the velocity of cold water in the experiment, then rise and return to stability.

Results of the experiments compared between the smooth pipes (Exp. 3) and with helical pipes (Exp. 4), shown in table 6, that results indicate the insert of a twisted tape (helical pipe) to the heat exchanger, leads to an increase in the effectiveness of the conductivity of heat transfer, where the proportion ranged increase in the effectiveness of 10-19% compared with the smooth pipes see figure 6-5.

*Table 7-1: Compare the effectiveness of the heat transfer rate of the smooth tube and tube with the tape.*

| GREY WATER VELOCITY | COLD WATER VELOCITY | SMOOTH PIPE | HELICAL PIPE |
|---|---|---|---|
| | | Eff.% | EFF.% |
| Q1 | q1 | 26 | **34** |
| | q2 | 26 | **37** |
| | q3 | 31 | **43** |
| | | | |
| Q2 | q1 | 26 | **32** |
| | q2 | 27 | **36** |
| | q3 | 31 | **48** |
| | | | |
| Q3 | q1 | 25 | **29** |
| | q2 | 26 | **36** |
| | q3 | 29 | **48** |

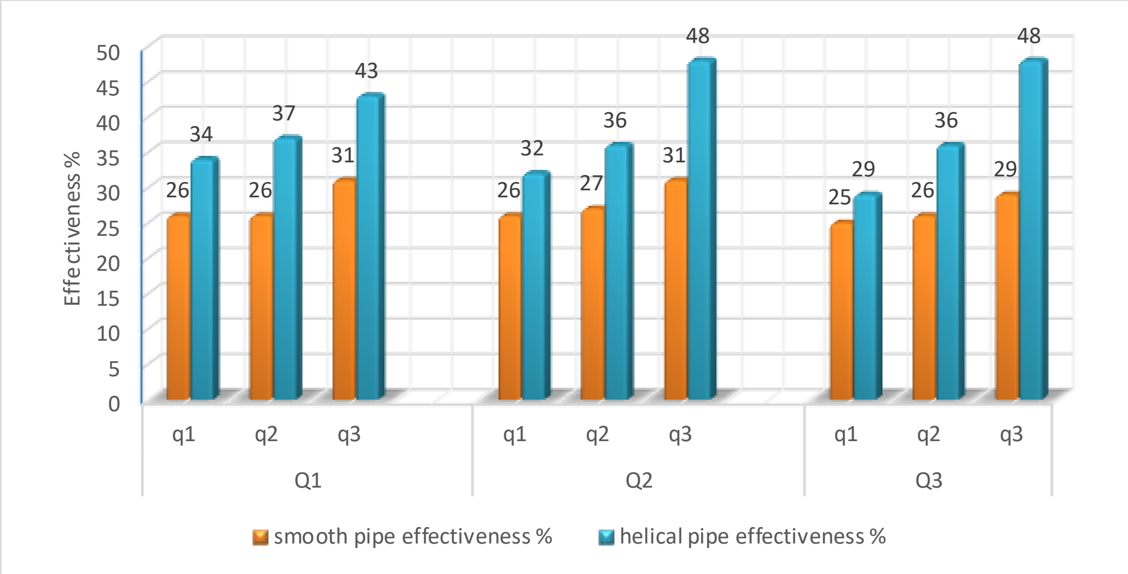



*Figure 7-1. The Comparison of the effectiveness of heat transfer between the smooth pipe for the third Exp. and helical pipe for the fourth Exp. for the heat recovery system.*

the results of the PIV technique are compared for the cases with smooth pipes, the case with twist tape (helical screw tape) provides a very non-uniform velocity distribution, the higher velocity being recorded it to the top free surface, while a lower velocity is achieved in the region of the wings (twist tape). The velocity will decrease near the twisted tape because of the impact it on the velocity of greywater, the lowest velocity at the Q3 compare to the Q2, Q1.

The velocity map distribution for the case when the greywater flow rate is Q2 (value of flowrate) and we have q1, q2, q3, for the cold water. Looking at these results from the PIV technique can be concluded that the temperature cold water flow rate does not have an effect on the velocity distribution of the greywater.

The vector map distribution, one important remark is regarding the vortices formed behind the wings. In the upper half of the map, the Velocity on the x-axis is dominant, so the majority of these vectors are directed to the outlet. Decreasing, the other two velocity components have a greater influence, leading to stagnation areas see figure (6-6).

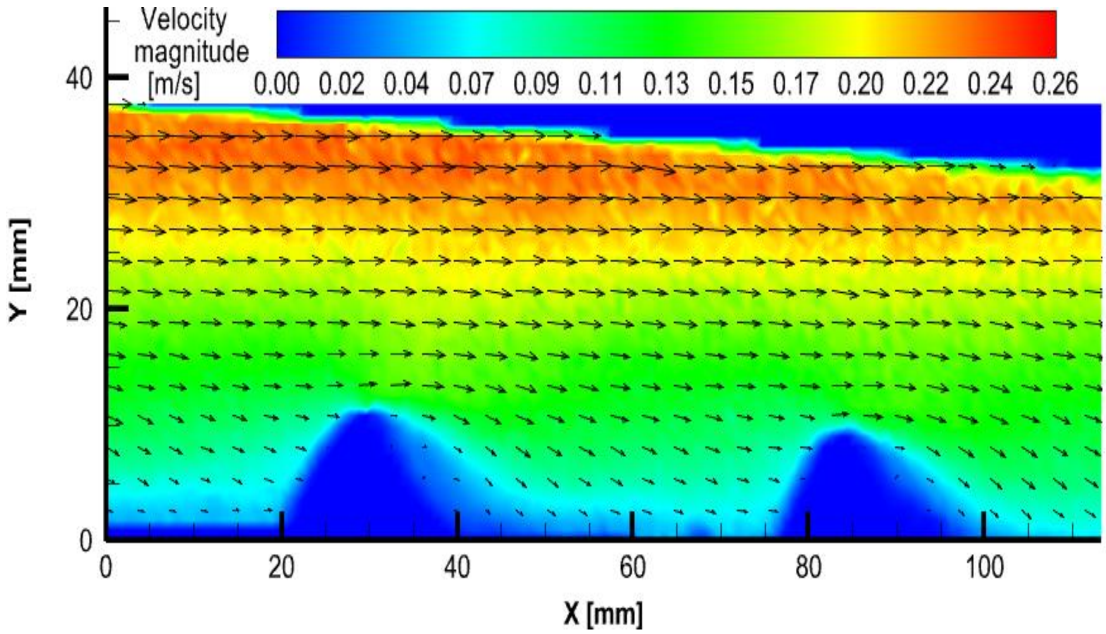



*Figure 7-2. Focused velocity distribution map and vector distribution on the copper pipe with helical screw tape for Q2 of the greywater with q2 of the cold water*

The temperature distribution achieved between copper smooth pipes and along the numerical model, **the temperature is highest at the inlet and <u>decreases</u> at the outlet, due to heat recovery (heat transfer from hot gray water to cold water).**

The temperature distribution achieved on the copper smooth pipe and along the numerical model, **the temperature is highest at the inlet and decreases at the outlet, the cold water temperature <u>increases</u> at the outlet, due to heat recovery (heat transfer from hot gray water to cold water).**

The findings of the temperature distribution in the locations of the thermocouples were acquired by numerical simulation and experiment, the velocity distribution on the copper pipe and between them were acquired by numerical simulation and PIV technique experiment, and the experimental results are well consistent with the numerical simulation.

The dual heat exchanger divides the flow into two pipes, reducing flow rate velocity and improving heat transfer efficiency.

This method is simple to use and inexpensive to implement. It can be planned and installed in the multi-story building's basement.

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