Experimental study on the heat recovery from waste water systems

COORDONATOR DOCTORAT:

PROF.DR.ING. ILINCA NASTASE

PROF.DR.ING. MIHNA SANDU

STUDENT DOCTORAND:

DRD.ING. AMJED M.S. ALBAIYATI

Second report

2019

Contents

Chapter One_Introduction 5
1.1- Introduction 6
Chapter Two_Free Surface Flow And Heat Exchanger 9
2.1- Motion with free surface in the channel and pipes 10
2.1.1- General. Energetic study. 10
2.2- Uniform flow in Channel 14
2.2.1- The Manning Equation 16
2.2.2- The Chezy formula 17
2.3- Heat exchanger 17
2.3.1- The Counterflow Heat Exchanger 19
Chapter Three Measurement Techniques 21
3.1- Experimental techniques 22
3.1.1- Flow rate measurements 22
3.1.1.1- Measurement techniques 22
3.1.1.2- ultrasonic principle technical 22
3.1.1.3- Transport PT900 Advantages 22
3.1.1.4- Install the device 23
3.1.1.5- Viewing the Traverse Configuration 24
3.1.1.6- Viewing the Transducer Spacing 25
3.1.2- Data logger ALMEMO® 710 25
3.1.2.1- Process control 27
3.1.2.2- Date and time-of-day 27
3.1.2.3- Output cycle 28
3.1.2.4- Cycle factor 28
3.1.2.5- Averaging over measuring channel scans 28
3.1.2.6- Conversion rate 28
3.1.2.7- Scan cycle 28

3.1.2.8- Measured value memory 28
3.1.2.9- Numbering of measuring operations 29
3.1.2.10- Control inputs and outputs 29
3.1.2.11- Operation 29
3.1.2.12- Output 29
3.1.2.13- Thermocouples 30
3.1.3- Particle image velocimetry (PIV) 30
3.1.3.1- The Principle of PIV 31
3.1.4- Laser Doppler Velocimetry (LDV) 32
3.1.4.1- Introduction 32
3.1.4.2- Principles of LDV 32
3.1.4.3- Benefits 33
3.1.4.4- Limitations 33
3.1.4.5- Applications 34
Chapter four Experimental 36
3- Experimental 37
3.1- First experiment: 37
3.1.1- Heat exchanger 38
3.1.2- Measurement tools 39
3.1.3- Display data 42
3.1.4- Results 42
3.2- Final Experimental Setup - Scope, technology, Objectives 43

Table of figures

Figure 1.Different levels for waste water heat recovery. 7
Figure 2. Different location for heat exchanger. 8
Figure 3. Free surface Channel and pipe 10
Figure 4.the force of gravity acting on a fluid particle moving along a streamline 12
Figure 5.The special case of a flow with a Froude number of unity 12
Figure 6.Elementary wave traveling on the surface of a fluid 13
Figure 7.Production of a single elementary wave in a channel as seen by a stationary observer. (b) Wave as seen by an observer moving with a speed equal to the wave speed 14
Figure 8.uniform flow in open channel (b) forces on a segment of channel having uniform flow[9]. 15
Figure 9.Overall energy balances for the hot and cold fluids of a two-fluid heat exchanger. 18
Figure 10.Temperature distributions for a counterflow heat exchanger. ... 20
Figure 11.Fixture Placed on Top of Pipe. 23
Figure 12.Fixture Rotated to Horizontal Position. 24
Figure 13.Fixture Rotated to Horizontal Position. 24
Figure 14.Transducer Spacing Value. 25
Figure 15.New digital ALMEMO® D7 sensors. 26
Figure 16. data logger operation. 27
Figure 17.Principle of particle image velocimetry technique consisting on flow, flow seeding, laser, camera, synchronizer and computer. 31
Figure 18.An overview showing the principle of Dantec Dynamics' 2D PIV systems. 32
Figure 19.Measuring principle of the Laser-Doppler Velocimetry. 34
Figure 20.Laser Doppler Optical System 35
Figure 21.the first experiment unit 37
Figure 22.Schematic representation of the first experimental unit. 38
Figure 23. Heat exchange unit. 39
Figure 24.Simplified diagram of the final installation heat exchanger...... 39
Figure 25.Ultrasonic Flow Meter for Liquids. 40
Figure 26.Thermocouples and data logger. 41
Figure 27.the relationship between the total rate of heat transfer and discharge. 43
Figure 28.Section of the experimental demonstrator. 44
Figure 29. on left on-demand DWHR, on the right storage DWHR. 46
Figure 30.Experimental setup of proposed DWHR unit. 46

Table 1. data temperature and flow rate..42

Nomenclature	
$T_{h,i}$	Temperature hot water inlet
$T_{h,o}$	Temperature hot water outlet
$T_{c.i}$	Temperature cold fresh water inlet
$T_{c,o}$	Temperature cold fresh water outlet

Chapter One

Introduction

1.1- Introduction

One of the main challenges in the world today is reducing energy consumption and CO_2 footprint in existing buildings without major construction work. Many of these buildings represent heritage buildings and the intervention constraints on the original building are much more restrictive for these particular cases. The building sector is one of the world's largest energy consumers, so it is important to seek out and use recovery energies for individual consumers. The main component of energy consumption in buildings is heating, but the demand for the domestic hot water is also very high, especially when daily consumption is high and especially for specific applications (hotels or laundries for example) This is why the implementation of technologies using renewable energy and recovery sources for water heating[1] has become very important and one of these technologies involves the recovery of the thermal energy from wastewater. Usually, heat recovery from wastewater is designed to recover residual energy from the hot drainage water and this recovered energy is used to preheat incoming cold water or to heat pumps.

Wastewater heat recovery applications are becoming widespread in energy saving applications. This interesting technology is an efficient and inexpensive way to recover thermal energy for reuse also in facilities systems in buildings, such as the production of sanitary hot water or heating. It is known that a sustainable and low emissions operation in air conditioning and heating processes is achieved by harvesting the otherwise wasted energy in wastewater through specially designed heat exchangers, lying at the core of heat pumps. This combined system is called wastewater source heat pump.

The scope of this thesis is to reduce the energy consumption and CO_2 footprint in buildings by recovering the waste heat from the wastewater systems using smart energy efficient heat exchangers

We present here a short state of the art of the heat recovery from wastewater as it known at the moment. The literature [2-6] stated that the concept of heat recovery from wastewater could be considered highly diversified and the ways of making use of the available heat are many. The global system is divided into three levels. Level 1 represents the wastewater system, all the way upstream from the water consumption to the final effluent from the waste water treatment plant, where the potential heat resource exists. Level 2 is the transferring system that connects Level 1 and Level 3, i.e. the technical system that provides heat from resource to the final demand. Finally, Level 3 is the receiving system, i.e. where the heat is finally to be reclaimed. Figure 1 depicts an overall view of the different system levels and its diversified sections. It can be seen from picture 1 that such a system could be used inside a building, outside on the sewer system upstream or downstream the wastewater treatment plant.

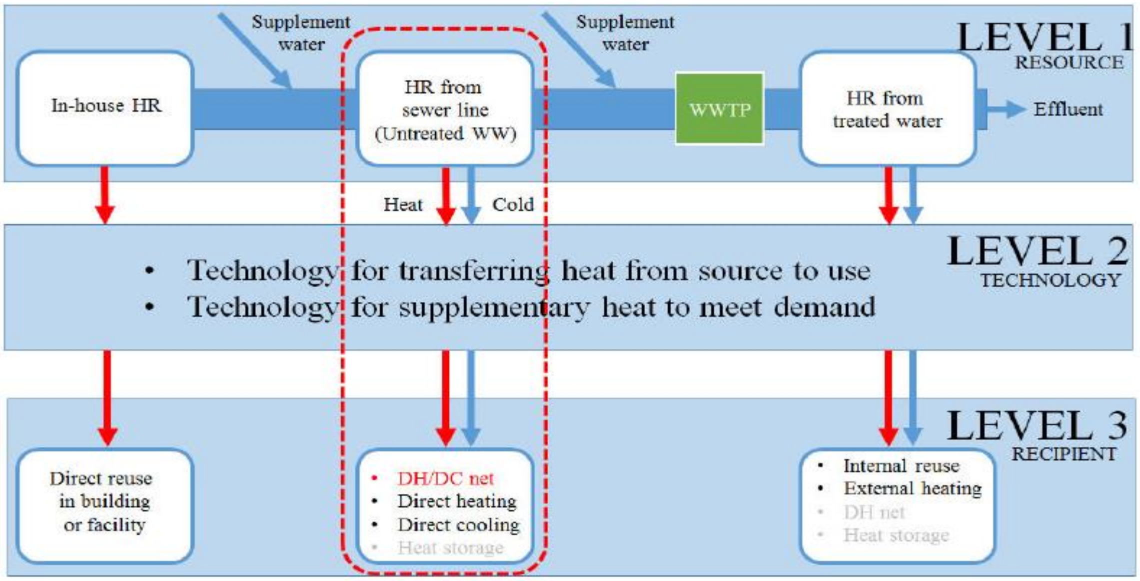


Figure 1.Different levels for waste water heat recovery.

The energy recovered from such a system can be used directly to a specific facility (this is the case for the heat exchangers installed just before the showers) or indirectly via a heat pump. Culha et al. [7] have conducted a review where the wastewater heat exchangers are classified in detail based on multiple features, including utilization and construction methodology. These heat exchangers can be used in three different locations (see figure 2) to recover the heat from the wastewater: the first location is inside the building and it is called domestic utilization, the second location is outside and provides larger excess heat from the wastewater to ensure heating/cooling for multiple buildings. Apart from these two locations, waste water heat exchangers can be installed downstream of a wastewater treatment plant to efficiently utilize the energy in the treated waste water at a larger scale. The heat recovery at the sewage treatment plant is technically easier since the energy from the treated wastewater can be extracted more efficiently.

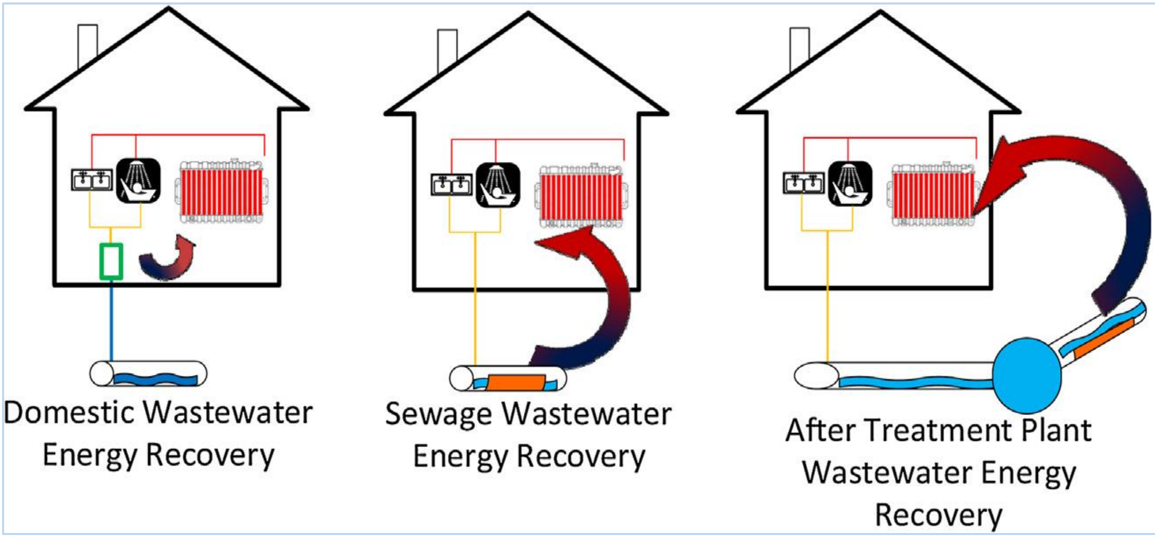


Figure 2. Different location for heat exchanger.

Chapter Two

Free Surface Flow And Heat Exchanger

Motion with free surface in the channel and pipes

2.1.1- General. Energetic study.

When moving with the free surface the live section of the current is in direct contact with the atmosphere. Such movement can be done in the channels (Figure 3, a) or in the pipes (Figure 3, b) being characterized, as well as the pressure movement, by the number of l Reynolds. It is reminded that this is a non-dimensional complex related to the action of the viscous friction forces and, for the movement with the free surface, it has the expression:

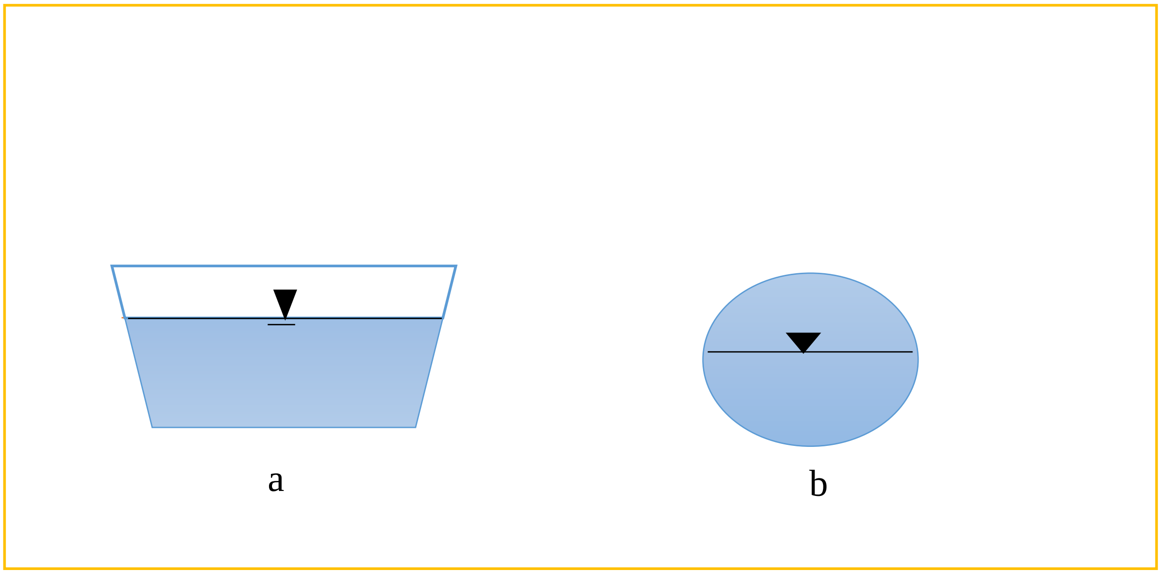


Figure 3. Free surface Channel and pipe

$$Re = \frac{\upsilon R}{\nu} \tag{1}$$

Where:

υ: mean velocity

R: hydraulic radius

ν: Kinematic viscosity

Analog with movement under pressure, the flow with free surface is laminar $Re < Re_{cr}$and turbulent for $Re > Re_{cr}$. The value Re can be obtained knowing (Re ≅ 2300), on the pipes. Considering that the $R = \frac{4}{D}$ result $Re_{cr} =$

$\frac{(Re_D)_{cr}}{4} \cong 575.$ Experimental Zegjda confirmed this value, showing that the passage from the turbulence Iaminara movement shall be carried out in a specific area of transition .

For channels very broad $R \cong h\,(h - borders\,on\,a\,current),$ and the number of Reynolds becomes.

$$Re = \frac{vh}{\nu} \tag{2}$$

Laminara movement can only occur in the channel and very low speeds, and has reduced technical applications. In all other cases, the movement is turbulence.

Free surface movement is another dimensionless parameter that expresses the influence of the weight forces- Froude number expressed by the expression

Froude number defined as where

V is a velocity, *g* the acceleration of gravity, and _ a length.

$$Fr = \frac{v^2}{gh}, \tag{3}$$

That is the double the ratio between the kinetic energy and the potential energy of the flow. Sometimes, in literature, the expression is used (3):

$$\overline{Fe} = \frac{v}{\sqrt{gh}} \tag{4}$$

Fr $\frac{\boldsymbol{inertia\,force}}{\boldsymbol{gravitational}}$ **(**Flow with a free surface)[8]

The Froude number is an index of the ratio of the force due to the acceleration of a fluid particle to the force due to gravity (weight). This can be demonstrated by considering a fluid particle moving along a streamline (Fig. 4).

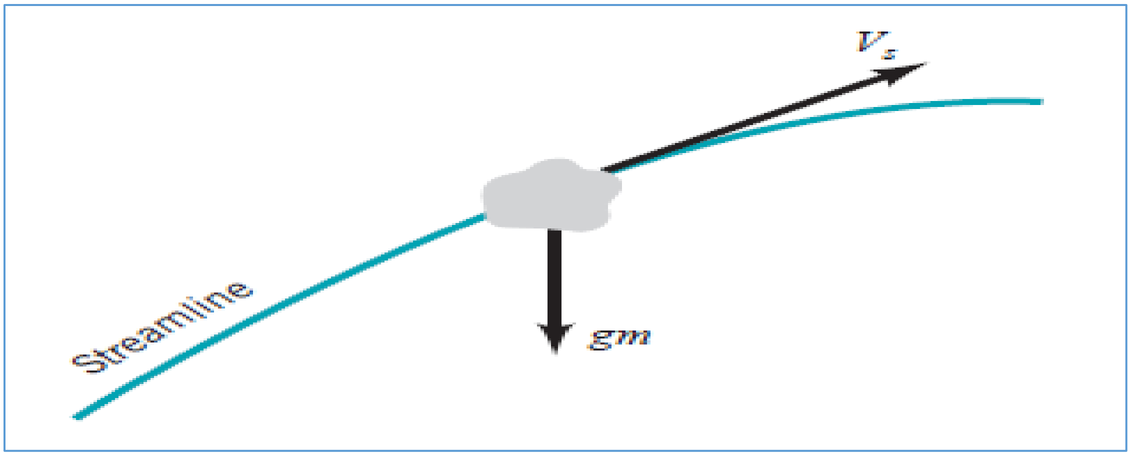


Figure 4.the force of gravity acting on a fluid particle moving along a streamline[8]

The special case of a flow with a Froude number of unity, is termed a ***critical flow.*** If the Froude number is less than 1, the flow is ***subcritical*** or (*tranquil)*. A flow with the Froude number greater than 1 is termed ***supercritical*** or (*rapid)* show (figure 5) [8].

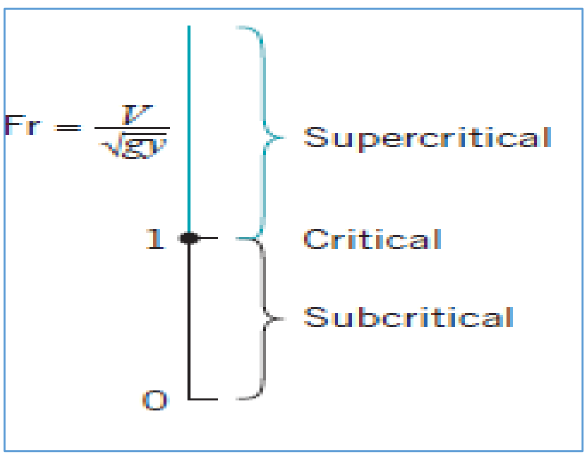


Figure 5.The special case of a flow with a Froude number of unity

Consider an elementary wave traveling on the surface of a fluid, as is shown in the (figure 6, 7) and If the fluid layer is stationary, the wave moves to the right with speed *c* relative to the fluid and the stationary observer. If the fluid is flowing to the left with velocity v < c, the wave (which travels with speed *c* relative to the fluid) will travel to the right with a speed of c – v relative to a fixed observer. If the fluid flows to the left with v = c the wave will remain stationary, but if v > c the wave will be washed to the left with speed v – c.

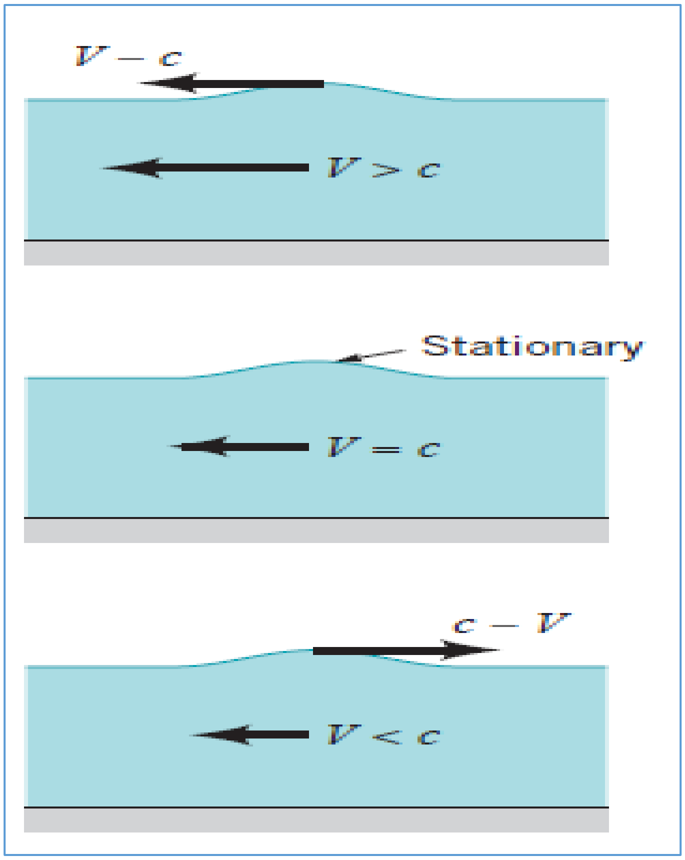


Figure 6.Elementary wave traveling on the surface of a fluid

The above ideas can be expressed in dimensionless form by use of the Froude number,$Fr = V/\sqrt{gy}$ where we take the characteristic length to be the fluid depth, *y*. Thus, the Froude number $Fr = V/\sqrt{gy} = V/c$ is the ratio of the fluid velocity to the wave speed.

The following characteristics are observed when a wave is produced on the surface of a moving stream, as happens when a rock is thrown into a river. If the stream is not flowing, the wave spreads equally in all directions. If the stream is nearly stationary or moving in a tranquil manner (i.e., $V < c$), the wave can move upstream. Upstream locations are said to be in hydraulic communication with the downstream locations. That is, an observer upstream of a disturbance can tell that there has been a disturbance on the surface because that disturbance can propagate upstream to the observer. Viscous effects, which have been neglected in this discussion, will eventually damp out such waves far upstream. Such flow conditions, $V < c, or\ Fr < 1$or are termed ***subcritical***.

On the other hand, if the stream is moving rapidly so that the flow velocity is greater than the wave speed (i.e.,$V > c$), no upstream communication with downstream locations is possible. Any disturbance on the surface downstream from the observer will be washed farther downstream. Such conditions, $Fr > c\ or Fr > 1$, are termed *supercritical*. For the special case of $V = c$ or$Fr = 1$, the upstream propagating wave remains stationary and the flow is termed *critical[8]*.

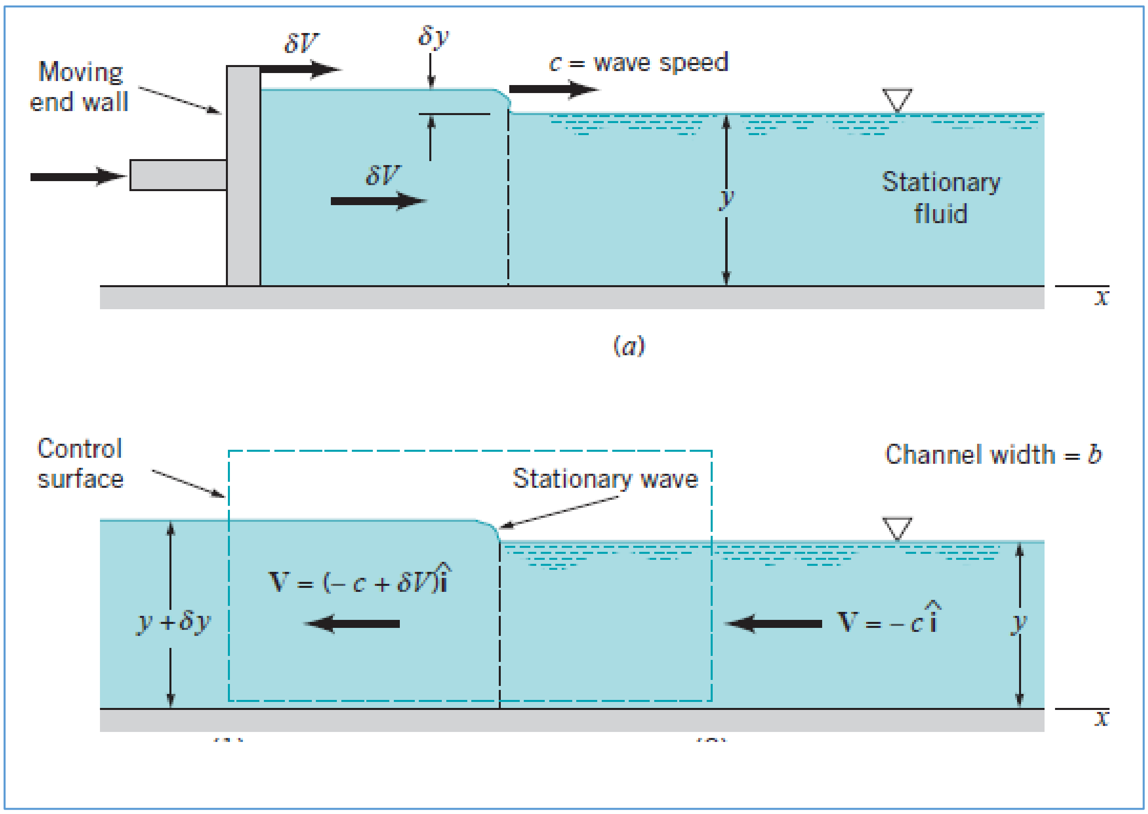


Figure 7.Production of a single elementary wave in a channel as seen by a stationary observer. (b) Wave as seen by an observer moving with a speed equal to the wave speed

Uniform flow in Channel

When water flows in an open chanal resistance is offered to it, which result in causing a loss of energy. The resistance encounterd by flowing water is generaly counteracted by the components of gravity force acting on the body of the water in the direction of motion show (figure 8)[9].

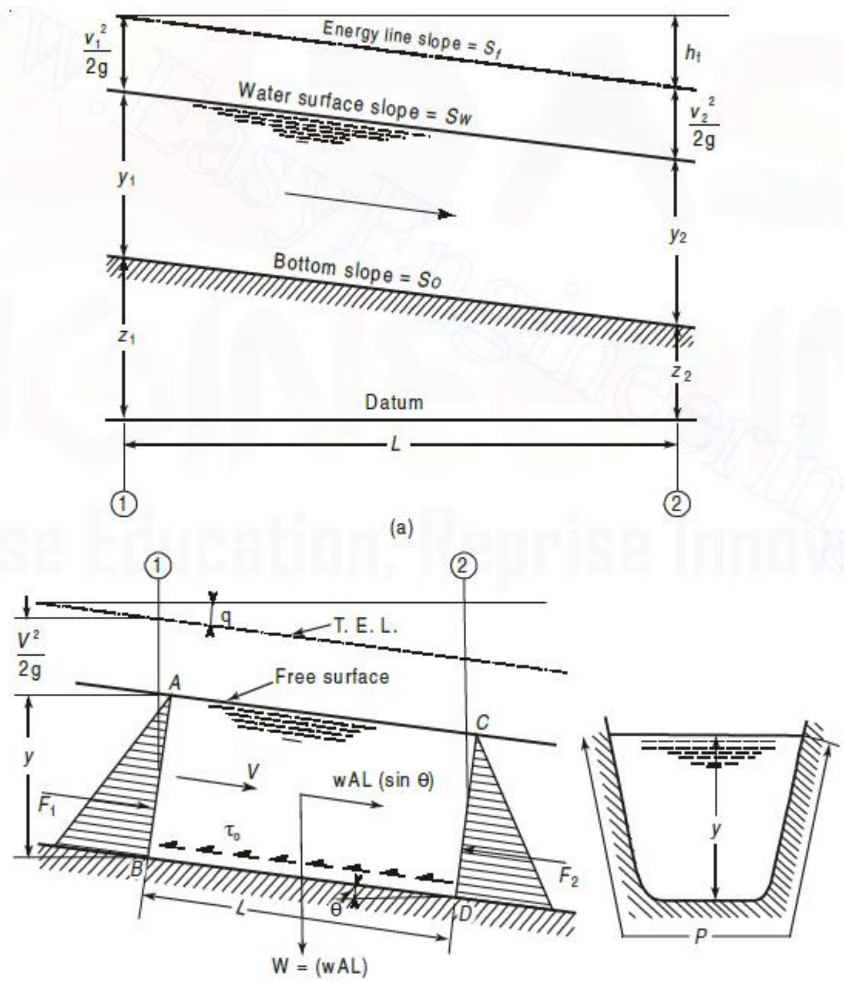


Figure 8.uniform flow in open channel (b) forces on a segment of channel having uniform flow[9].

When water flows in an open chanael resistance is offered to it, which result in causing a loss of energy. The resistance encounterd by flowing water is generaly counteracted by the components of gravity force acting on the body of the water in the direction of motion.

When water enters the chanal, the velocity and hence the resistance are smaller than the gravity force, which results im an acceleration flow in the upstream reach of the chanael.

Sereval *uniform-flow formulae* have been developmed which correlate the mean velosity of uniform flow in the open chanaels with the hydrulic radius, energy line slope and factor of flow resistance.

The most widely used uniform-flow formulae are the Chezy and manning formulae which are discribed in the flowing paragraphs[9].

The mean feature of uniform flow in a chanael can be summarrized as fllowing:

1- The depth of flow. Wetted area, velosity of flow and discharge are constant at evry section along the chanael reach.
2- The total energy line, water surface and chanael battom are all parallel.

2.2.1- The Manning Equation

In 1891, another Frenchman, Flamant attributed wrongly to the Irishman R. Manning that C varies with the sixth root of R, although Gauckler in 1868 had proposed the same hypothesis for flat slopes and also Hagen in 1881 attributed the same concept to any slope [10].

$$C = \frac{R^{\frac{1}{6}}}{n} \quad \text{......(5)}$$

From which

$$V = \frac{1}{n} R^{\frac{2}{3}} \sqrt{S} \quad \text{......(6)}$$

where: n is the characteristics of the surface roughness alone and the unit of length used is meter. In 1911 Buckly converted this equation to the foot second unit as

$$V = \frac{1.486}{n} R^{\frac{2}{3}} \sqrt{S} \quad \text{......(7)}$$

This equation is known in the English speaking world as the Manning equation, although on the continent of Europe it is sometimes known as strickler's equation. The Manning equation has proved most reliable in practical and extremely popular in western countries In order to relate the Manning coefficient (n) and the equivalent particle size (k), Strickler's empirical formula (1923) was used as (Henderson, 1966):

$$k = (n/0.034)^6 \quad \text{......(8)}$$

In which (k) in feet

2.2.2- The Chezy formula

In 1768, Antoine Chezy (Rouse, 1957), an engineer of the French Bureau of Bridges and Streets was given the task of designing a canal for the Paris water supply. He reasoned that the resistance would vary with the wetted perimeter and with the square of velocity, and the force to balance this resistance would vary with the area of cross section and with the slope. Therefore, he reasoned that $V^2 P/(A S)$ or $V^2/(R S)$ would be constant for any one channel and would be the same for any similar channel. His manuscript was not published until 1897, but his method gradually became known, and the square root of the preceding ratio came to be known as the ***Chezy*** coefficient[10]
The formula can be written as:

$$V = C\sqrt{RS} \quad \text{……(9)}$$

Where:

V : velocity of water;

C : Chezy's coefficient;

R : hydraulic radius; and

S : bed slope.

Heat exchanger

To design or to predict the performance of a heat exchanger, it is essential to relate the total heat transfer rate to quantities such as the inlet and outlet fluid temperatures, the overall heat transfer coefficient, and the total surface area for heat transfer. Two such relations may readily be obtained by applying overall energy balances to the hot and cold fluids, as shown in (Figure 9). In particular, if q is the total rate of heat transfer between the hot and cold fluids and there is negligible heat transfer between the exchanger and its surroundings, as well as negligible potential and kinetic energy changes, application of the steady flow energy equation, gives.

$$q = \dot{m}_h(i_{h,i} - i_{h.0}) \quad \text{……(10)}$$

And

$$q = \dot{m}_c(i_{c,o} - i_{c,i})\ldots\ldots(11)$$

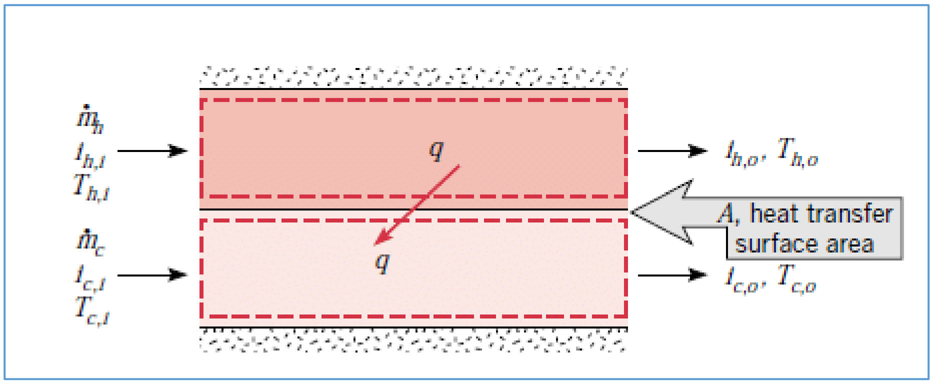


Figure 9.Overall energy balances for the hot and cold fluids of a two-fluid heat exchanger.

where *i* is the fluid enthalpy. The subscripts *h* and *c* refer to the hot and cold fluids, whereas *i* and *o* designate the fluid inlet and outlet conditions. If the fluids are not undergoing a phase change and constant specific heats are assumed, these expressions reduce to

$$q = \dot{m}_h h_{p,h}(T_{h,i} - T_{h,o})\ldots\ldots(12)$$

And

$$q = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i})\ldots\ldots(13)$$

Another useful expression may be obtained by relating the total heat transfer rate *q* to the temperature difference ΔT between the hot and cold fluids, where

$$\Delta T = T_h - T_c$$

Such an expression would be an extension of Newton's law of cooling, with the overall heat transfer coefficient *U* used in place of the single convection coefficient *h*. However, since _*T* varies with position in the heat exchanger, it is necessary to work with a rate equation of the form

$$q = UA\Delta T_m\ldots\ldots(14)$$

we conclude that the appropriate average temperature difference is a *log mean temperature difference*, ΔT_{1m}Accordingly, we may write

$$\boldsymbol{q} = \boldsymbol{UA}\Delta \text{ ....}(15)$$

Where

$$\Delta T_{Im} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \text{..}(16)$$

2.3.1- The Counterflow Heat Exchanger

The hot and cold fluid temperature distributions associated with a counterflow heat exchanger are shown in (Figure 10). In contrast to the parallel-flow exchanger, this configuration provides for heat transfer between the hotter portions of the two fluids at one end, as well as between the colder portions at the other. For this reason, the change in the temperature difference, $\Delta T = T_h - T_c$ with respect to x is nowhere as large as it is for the inlet region of the parallel-flow exchanger. Note that the outlet temperature of the cold fluid may now exceed the outlet temperature of the hot fluid. Equations 12 and 13 apply to any heat exchanger and hence may be used for the counterflow arrangement. Moreover, it may be shown that Equations 14 and 15 also apply. However, for the counterflow exchanger the endpoint temperature differences must now be defined as:

$$\begin{bmatrix} \Delta T_1 \equiv T_{h,1} - T_{c,1} = T_{h,i} - T_{c,o} \\ \Delta T_2 \equiv T_{h,2} - T_{c,2} = T_{h,o} - T_{c,o} \end{bmatrix}$$

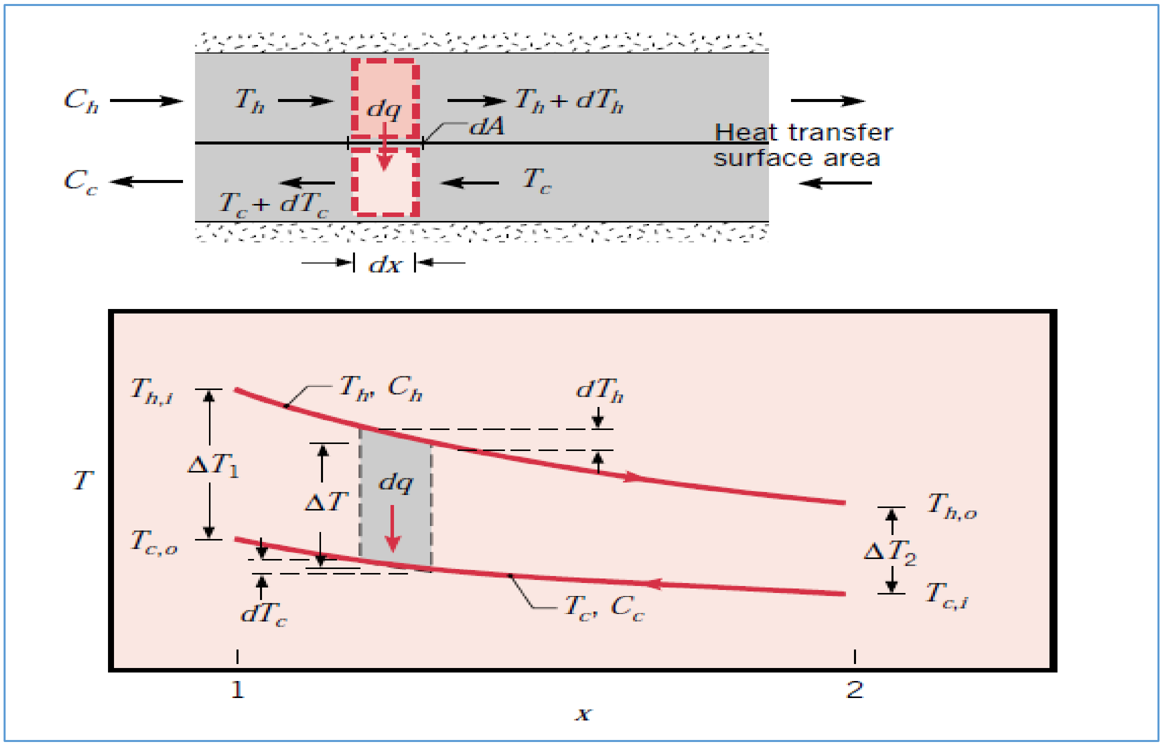


Figure 10.Temperature distributions for a counterflow heat exchanger.

Chapter Three

Measurement Techniques

3.1- Experimental techniques

3.1.1- Flow rate measurements

3.1.1.1- Measurement techniques

Energy recovery from waste water by heat exchanger counterflow, to measure the flow pipe in the cold or hot, so it uses a device ***(TransPort®PT900 Portable Ultrasonic Flow Meter for Liquids)***, which is easy to use device is installed on the pipe from the outside to measure the flow. The PT900 mobile transmitter is also placed in a durable rubber housing suitable for indoor and outdoor use. The device can also be placed in a solid load container or mounted on the pipe. To measure the temperature of hot gray water and cold water to know the efficiency of keeping heat energy from gray water to cold water we use a device ***(Data logger ALMEMO® 710).***

3.1.1.2- ultrasonic principle technical

Ultrasonic technologies are used for flow measurement in the form of collection of information and data pertaining to the traversed medium are used to measure volumetric flow rates in pipelines. Ultrasonic systems major benefits include non-invasiveness ease of operation and installation, quick response to change in flow, increased time between calibrations, and the modular design Transit-time flowmeters are used in a variety of applications, including the measurement of raw and treated water and in different stages of the treatment process such as the measurement of settled water, supernatant, backwash, and chemical additives[11].

3.1.1.3- Transport PT900 Advantages

- A wide selection of transducers suitable for most applications
- Wireless tablet for Bluetooth® communication with the transmitter
- Easy programming with bright touch screen and multiple-language user interface
- Fast-responding, high-accuracy transmitter with green/red light health indication and 8 GB of data logging storage
- Velocity, volume, mass, totalizer and energy flow rate measurements
- Easy-to-install clamping fixture.

3.1.1.4- Install the device

- Select a clamp –on fixture mounting location on the pipeline
- Place the clamp-on fixture on the top of the pipe so that minimal effort is required to maintain its position during installation shown in (figure 11).
- be sure that the scale markings on the rail rod of the clamp-on fixture can be easily read after the installation has been completed.
- The clamp-on fixture should be firmly mounted to the pipe, but it should still be loose enough to allow final alignment.
- Rotate the fixture to the 3 o’clock or 9 o’clock position on the pipe (show in Figure 12). Installation on the top or bottom of the pipe is not recommended. Make sure the pipe still rests in the cutout slot on the bottom of both end pieces, to ensure that the fixture is parallel to the pipe centreline.[12]

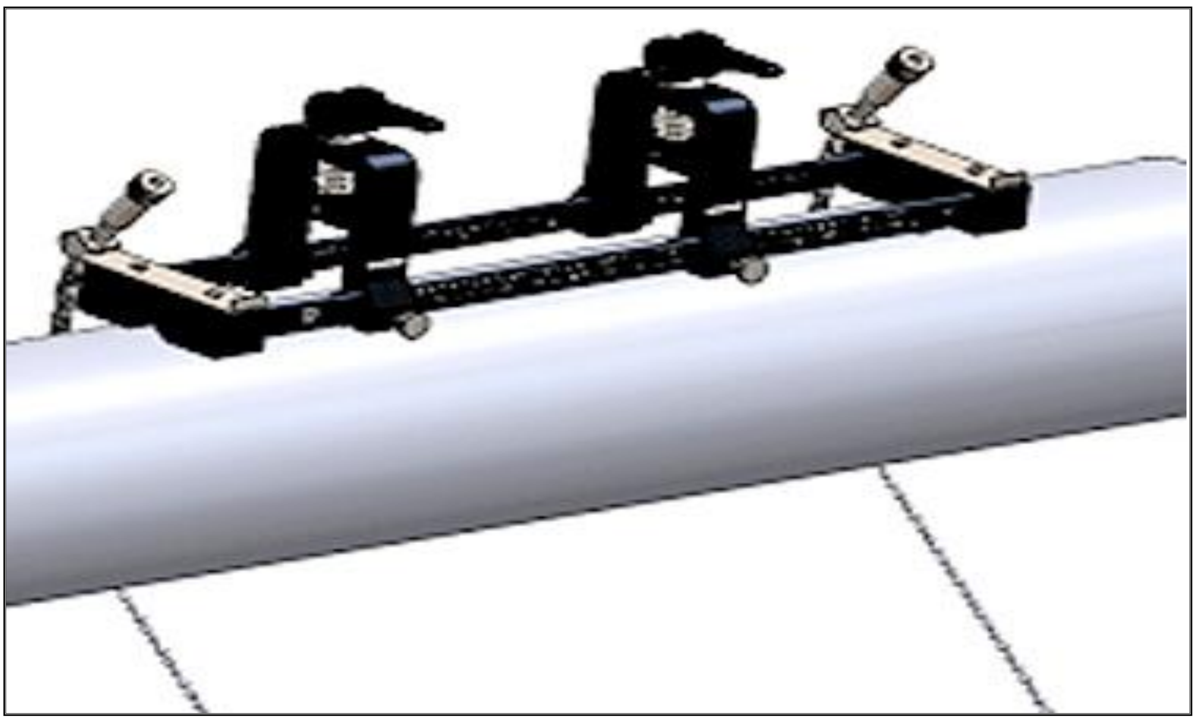


Figure 11.Fixture Placed on Top of Pipe.

Figure 12.Fixture Rotated to Horizontal Position.

3.1.1.5- Viewing the Traverse Configuration

For CLAMP-ON transducers, one of the six possible TRAVERSE configurations shown in (Figure 13) is displayed, as appropriate for your programmed transducer information. Typically, a two-traverse installation is used[12].

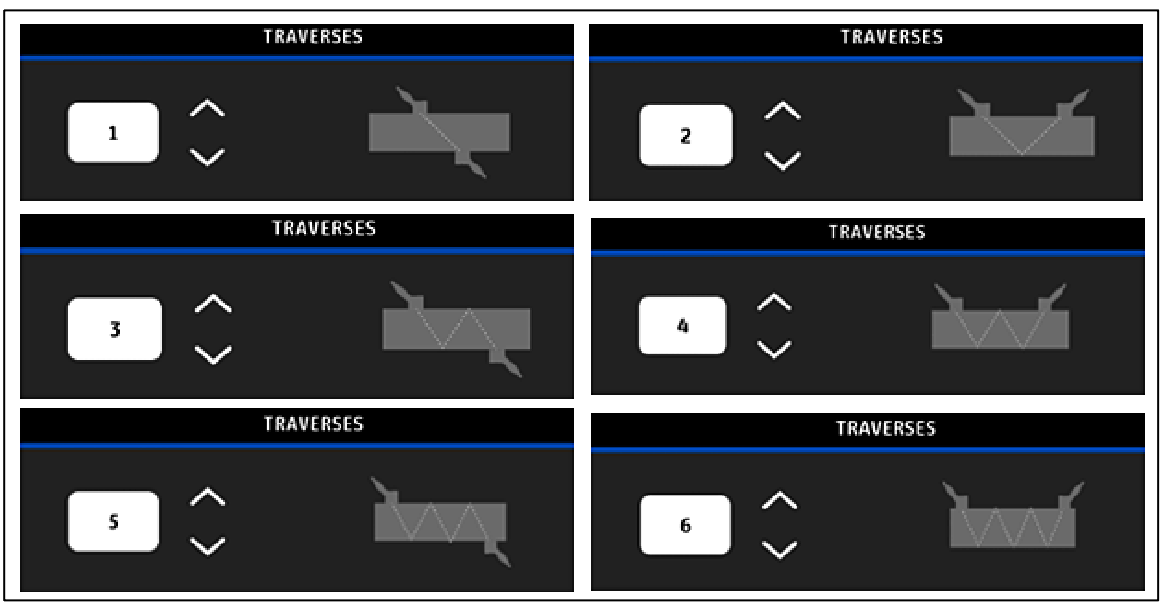


Figure 13.Fixture Rotated to Horizontal Position.

3.1.1.6- Viewing the Transducer Spacing

The TRANSDUCER SPACING screen shown in (Figure 14) shows the value calculated by the PT900 for the correct distance between the upstream and downstream transducers, based on your programmed transducer data. This value should be used when installing your transducer clamping fixture on the pipe[12].

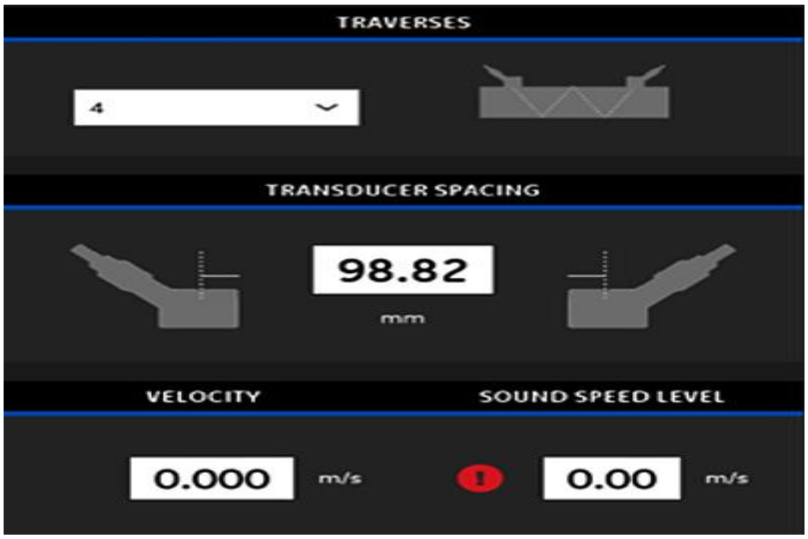


Figure 14.Transducer Spacing Value.

3.1.2- Data logger ALMEMO® 710

Data logger ALMEMO® 710 incorporates 10 measuring inputs shown in (figure 15). All new and already existing sensors designed for any measurable variable can be connected and evaluated. Sensors using analog signals pass via the integrated high-speed, high-resolution A/D converter. Digital D6 and the latest digital D7 sensors transfer their measured values to the measuring instrument direct in digital form. The measuring instrument supports all ALMEMO® plug connectors and sensor functions. Digital D6 / D7 sensors can be configured directly via the touchscreen[13].

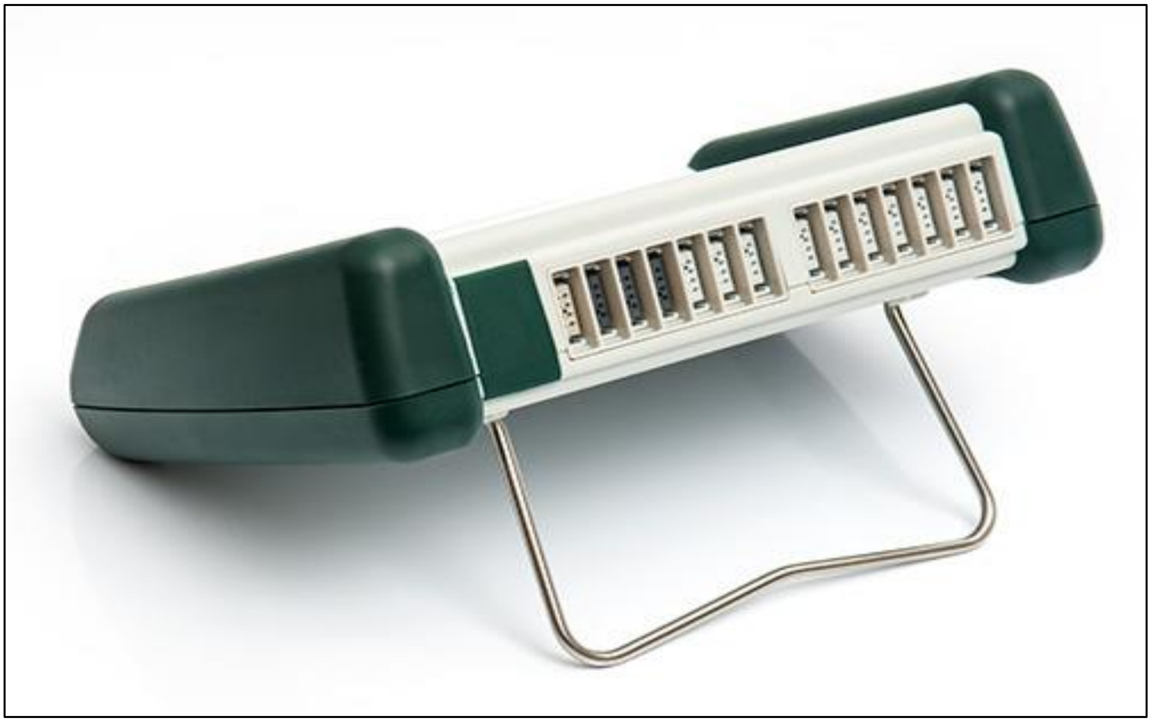


Figure 15.New digital ALMEMO® D7 sensors.

With these digital ALMEMO® D7 sensors the ALMEMO® system is enhanced by many new functions. They operate via an all-digital interface to the ALMEMO® 710 measuring instrument ensuring high-speed serial transmission of all measured values.

The measuring ranges of ALMEMO® D7 plugs are independent of the measuring instrument and can be expanded as and when required for new applications.

Measured values can be displayed with up to 8 digits (depending on range) and the units with up to 6 characters. Sensor designation and information can be up to 20 characters.
The ALMEMO® D7 sensor has its own processor. These all work in parallel at their sensor-specifi c sampling rate. D7 sensors thus attain very high measuring speeds in dynamic measuring operations. Scanning times on the ALMEMO® 710 can be set individually for quick-acting and slow-acting sensors.

The ALMEMO® D7 plug can process up to 10 channels for measured values and function values. This includes new applications, especially for multi-purpose sensors (e.g. Meteo sensors) and for linking up to complex third-party devices (e.g. chemical analysers, power analysers)[13].

3.1.2.1- Process control

In order to record the measured values from all connected sensors in digital form measuring channel scanning must be performed continuously with measured value output according to a time-based process control. The measuring operation can be started and stopped by means of the keypad, the interface, an external trigger signal, the real-time clock, or by a specified limit value in- fringement. The standard cycle, settable from 1 second up, ensures even, cyclic output. If a higher speed is required, standard sensor values can be out- put at the conversion rate; however, all sensors can now use the new scan cy- cle, which obtains measured values from each channel individually according to its own actual measuring duration shown in (figure 16)[13].

Figure 16. data logger operation.

3.1.2.2- Date and time-of-day

Each measuring operation can be accurately logged using the real-time clock in terms either of date and time-of-day or purely by actual measuring duration.

For the purposes of starting / stopping a measuring operation, the start / stop date and time-of-day can be programmed.

3.1.2.3- Output cycle

The output cycle can be programmed to any value between 1 second and 59 hours, 59 minutes, 59 seconds. This function permits cyclic output of measured values to the interfaces or to the memory and provides cyclic calculation of the average value.

3.1.2.4- Cycle factor

The cycle factor can be used to restrict data output from particular channels;

this may prove necessary in order to reduce excessive data flow especially

while measured data is being saved.

3.1.2.5- Averaging over measuring channel scans

The measured values from measuring channel scans can be averaged either over the whole fixed measuring period or over the specified cycle. These average values can then be output and saved on a cyclic basis to function channels provided for this purpose.

3.1.2.6- Conversion rate

All standard channels are scanned continuously at the conversion rate (2.5 / 10 / 50 / 100 measuring operations per second).

3.1.2.7- Scan cycle

With the ALMEMO® 710 there is also the superordinate scan cycle, which ac-quires all standard and D7 channels whenever these deliver a new current measured value. Recording can be accelerated if measured values thus acquired are stored to memory and / or output via the interface immediately.

3.1.2.8- Measured value memory

All measured values can be saved to a flash memory either manually or automatically per cycle or scan cycle. Memory capacity is 8 MB, sufficient for be- tween 400,000 and over 1.5 million measured values. This memory can be or- ganized and configured in either linear or ring form. All measuring operations found to have a modified sensor configuration are assigned a new numeric file name. Each measuring operation can also have a comments text attached; this can be up to 64 characters in length. Output is via the interface. Selection can be made according to file name, number, or date. Memory capacity can be increased substantially by using an external memory connector with a micro SD memory card. With an external memory connector (available as an accessory) files can be read out very quickly via any standard card reader.

3.1.2.9- Numbering of measuring operations

By entering a 6-digit number single scans or entire series of measuring operations can be identified and selectively read out from memory.

3.1.2.10- Control inputs and outputs

Up to 10 output relays or 4 analog outputs can be addressed individually via the touchscreen or via the interface with a relay trigger adapter . Via the trigger inputs it is also possible for external events to influence the measuring sequence.

3.1.2.11- Operation

All measured values and function values can be displayed in different menus on the touchscreen. For your individual applications user menus can be configured independently. The device can be operated via its state-of-the-art touch display. Sensors, device, and process control can thus be fully programmed.

3.1.2.12- Output

All measured data and programming parameters can be output to any peripheral equipment. The header can be programmed to refer specifically to your company or to a specific application. USB, RS-232, and Ethernet interfaces are available via the appropriate interface cables. To accommodate the variable data quantities and certain new parameters for operating D7 sensors the interface protocol has been changed so that data is now output in table format only; this can then as required be processed directly using any standard spreadsheet program.

3.1.2.13- Thermocouples

Thermocouples are temperature measurement sensors that generate a voltage that changes over temperature. Thermocouples are constructed from two wire leads made from different metals. The wire leads are welded together to create a junction. As the temperature changes from the junction to the ends of the wire leads, a voltage develops across the junction. Combinations of different metals create a variety of voltage responses. This leads to different types of thermocouples used for different temperature ranges and accuracies. Choosing a thermocouple often is a function of the measurement temperature range required in the application. Other considerations include the temperature accuracy, durability, conditions of use, and the expected service life[14].

3.1.3- Particle image velocimetry (PIV)

Particle image velocimetry (PIV) is a non-intrusive, full field optical measuring technique. PIV is used to obtain velocity information about fluid motion and has been applied to a many kinds of flows. In traditional PIV experiments, the fluid of interest is seeded with tracer particles, which are illuminated by a sheet of bright light. The positions of these particles at different times are recorded on a camera and the image sequence is digitized. Particle distance between two successive images ascertains the motion of the fluid. In multiframe/ single exposure PIV, two images revealing the positions of tracer particles within the fluid are taken at short time, Dt, apart[15]

To apply the PIV technique it is necessary to seed the fluid of interest with some kind of tracer particles. These particles will be illuminated by two consecutive short duration light pulses produced by a laser. The images of the particles are captured with a CCD camera as shown in figure 17). It is assumed that the motion of the tracer particles follows faithfully the movement of the fluid. Thus, the motion of the fluid can be determined by

measuring the particle displacements through evaluation of the PIV recordings. The recorded images are divided into small interrogation areas and analyzed by means of a correlation method. With the aid of PIV technique quantitative two-dimensional information of the fluid velocity is obtained.

Comprehensive descriptions and explanation on the principle of the PIV technique [16]

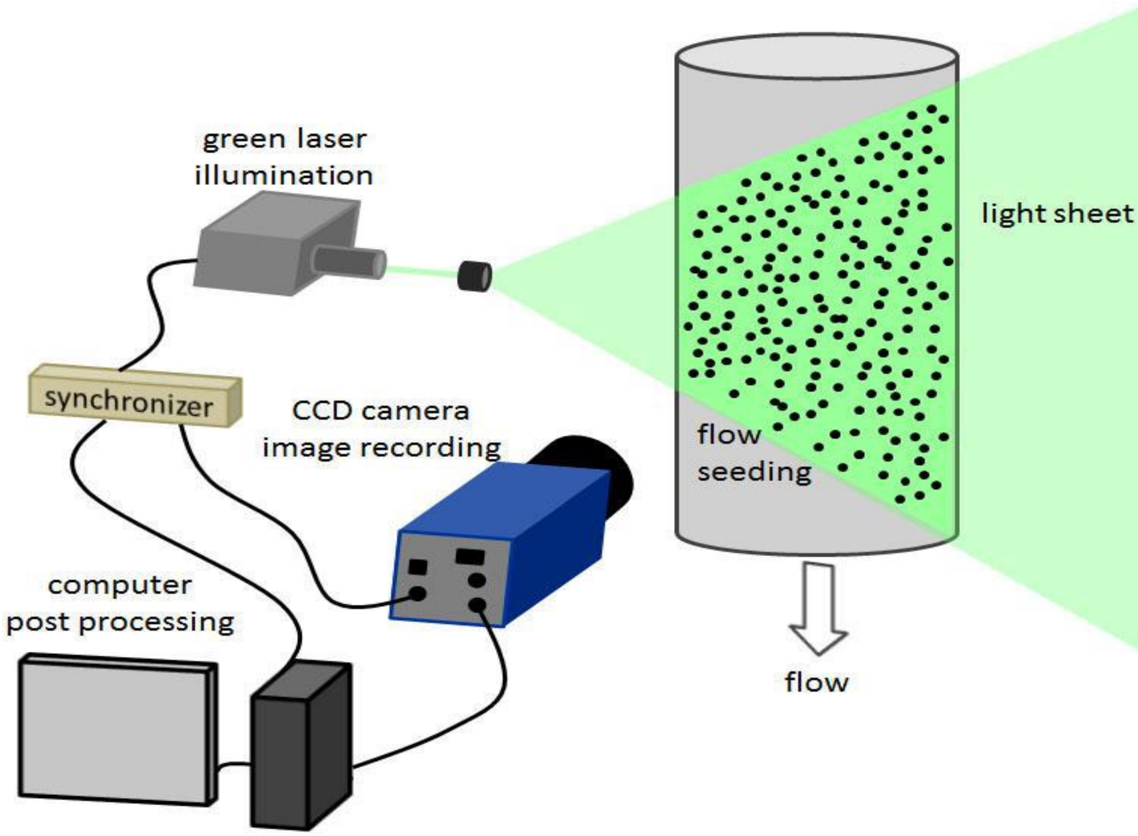


Figure 17.Principle of particle image velocimetry technique consisting on flow, flow seeding, laser, camera, synchronizer and computer[16].

3.1.3.1- The Principle of PIV

Two consecutive laser pulses illuminate a slice or volume of a flow field with particles suspended in the flow. The scattered light from the particles is recorded in two consecutive images on one or several digital cameras. The images are sub-divided into smaller areas for calculating the mean particle displacement between two corresponding sub-areas. The particle displacement is calculated using cross-correlation or Least Squares Matching techniques. Since the time between the laser pulses is known, the particle velocity can be determined. Taking into account the magnification of the optical setup, the absolute velocity field can be derived. The velocities calculated from an image pair are an instantaneous snapshot of the flow viewed by the cameras .PIV results are an accurate representation of the flow presented to the user and viewers in an easy to understand and visual manner. The presentation is aided by advanced soft-ware post-processing. PIV data for all three velocity components can be presented volumetrically. These capabilities have made PIV a popular and yet accurate research too shown in (figure 18)[17].

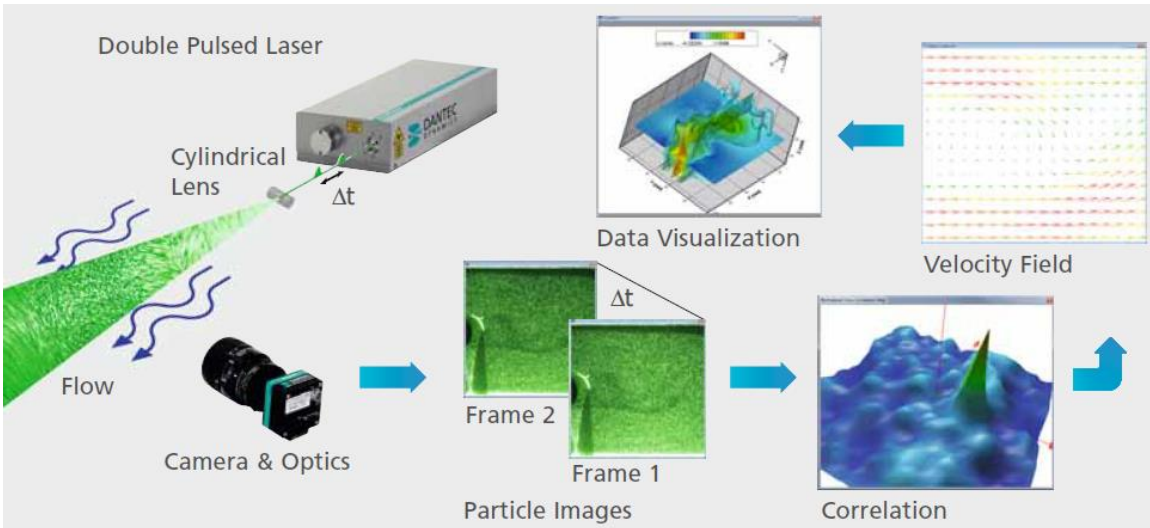


Figure 18.An overview showing the principle of Dantec Dynamics' 2D PIV systems.

3.1.4- Laser Doppler Velocimetry (LDV)

3.1.4.1- Introduction

The Laser-Doppler Velocimetry (LDV) is an optical measuring method which allows the determination of the velocity of a fluid with a very high temporal resolution. The velocity is measured virtually at one single point, referred to as measurement volume. Steady state as well as transient turbulent flow fields can, therefore, be investigated with a very high spatial accuracy. The measuring principle of LDV is based on the physical effect of Mie scattering Therefore, the flow has to be seeded with particles capable to follow the flow such that their movement reflect the motion of the flow well[18].

3.1.4.2- Principles of LDV

The LDV technique is based on the principle that light, scattered by a particle that is moving relatively to the light source, shows a frequency shift in comparison to the light source which is referred to as the Doppler effect. Although the measuring principle is always the same, many different types of LDV systems have been developed. The most common LDV technique is the dual-beam differential system, where a coherent light beam of the wavelength Λ is split equally. The resulting two beams, which are shown in (Figure 19,20), are brought to a focused crossing at a given angel ϑ which forms the measuring volume. A particle, traversing this volume, scatters light from the two light beams. Hence, this scattered light consists of two components, one corresponding to each beam. Both components obviously have a Doppler shift due to the velocity of the particle. The shift also depends on the direction of the light beam. Since the two beams are not parallel to one another, the two components of the scattered light have a slightly different Doppler shift[18].

3.1.4.3- Benefits

- Non-invasive measuring technique
- High accuracy
- No calibration required
- High data rates
- High spatial and temporal resolution
- Can be used in environments unsuitable for conventional techniques

3.1.4.4- Limitations

- Need transparent fluid and transparent walls
- Expensive equipment
- Needs to be seeded with particles
- Single point measurement
- Difficult to collect data near the walls

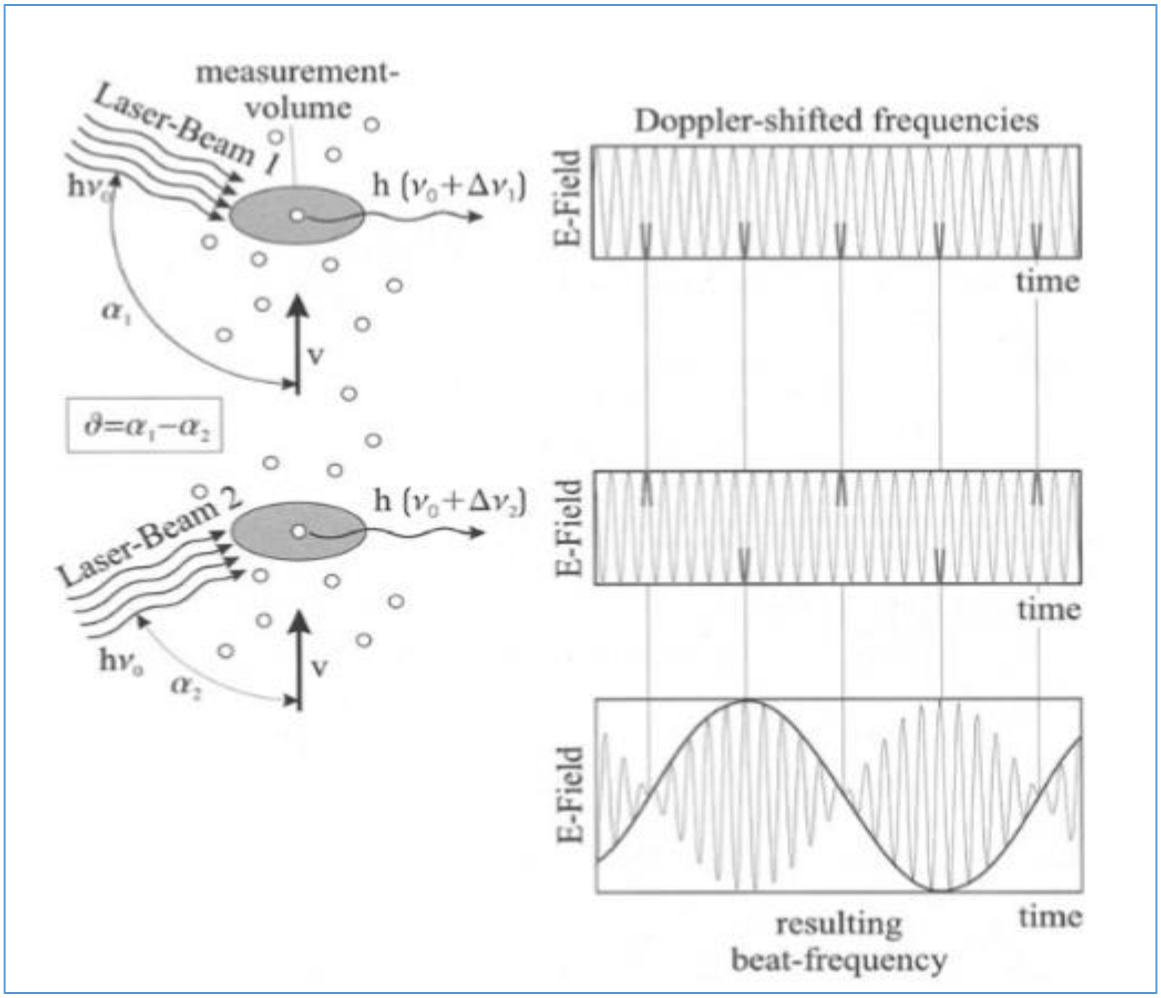


Figure 19.Measuring principle of the Laser-Doppler Velocimetry[19].

3.1.4.5- Applications

- Turbulent flow research
- Atmospheric turbulence
- Internal combustion engines, Turbines, etc.
- Aerodynamics, Supersonic flows, etc.
- Medical, biophysical, etc.
- Can be upgraded to PDPA for measuring droplet, spray size and velocities.

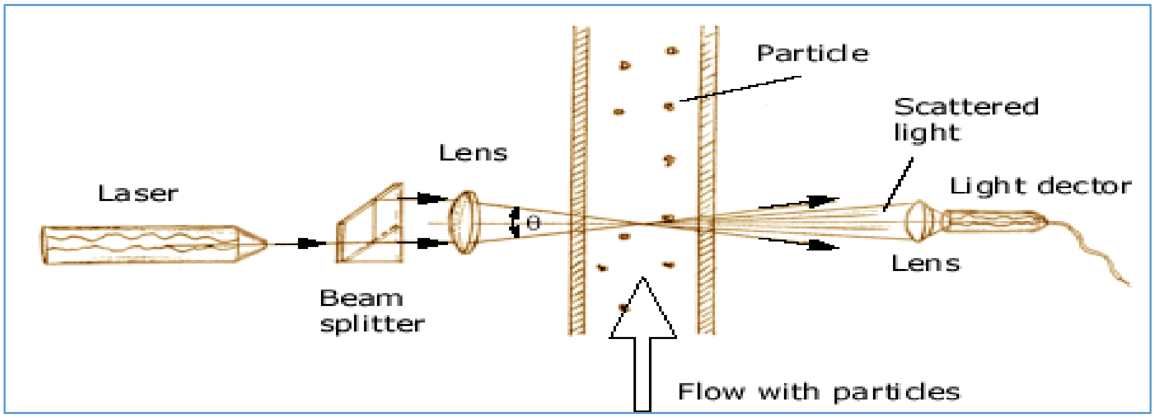


Figure 20.Laser Doppler Optical System

Chapter four

Experimental

3- Experimental

The experiment was set up in the CAMBI laboratory for faculty of building services engineering / UTCB. The experiment is division into two parts:

3.1- First experiment:

The experiment contains a bathtub with hot and cold water and heat exchange to heat recovery from gray water and tools of the measurement shown in (figure 21). The experiment is conducted by opening the cold fresh water tap to obtain a maximum discharge and measured by using (Ultrasonic Flow Meter for Liquids) and measure the temperature of the cold fresh water and gray water (wastewater) by using data logger (ALMEMO-710) to see how the effect of velocity different on the heat recovery (energy saving). a schematic diagram of the first experiment unit is shown in (figure 22).

Figure 21.the first experiment unit

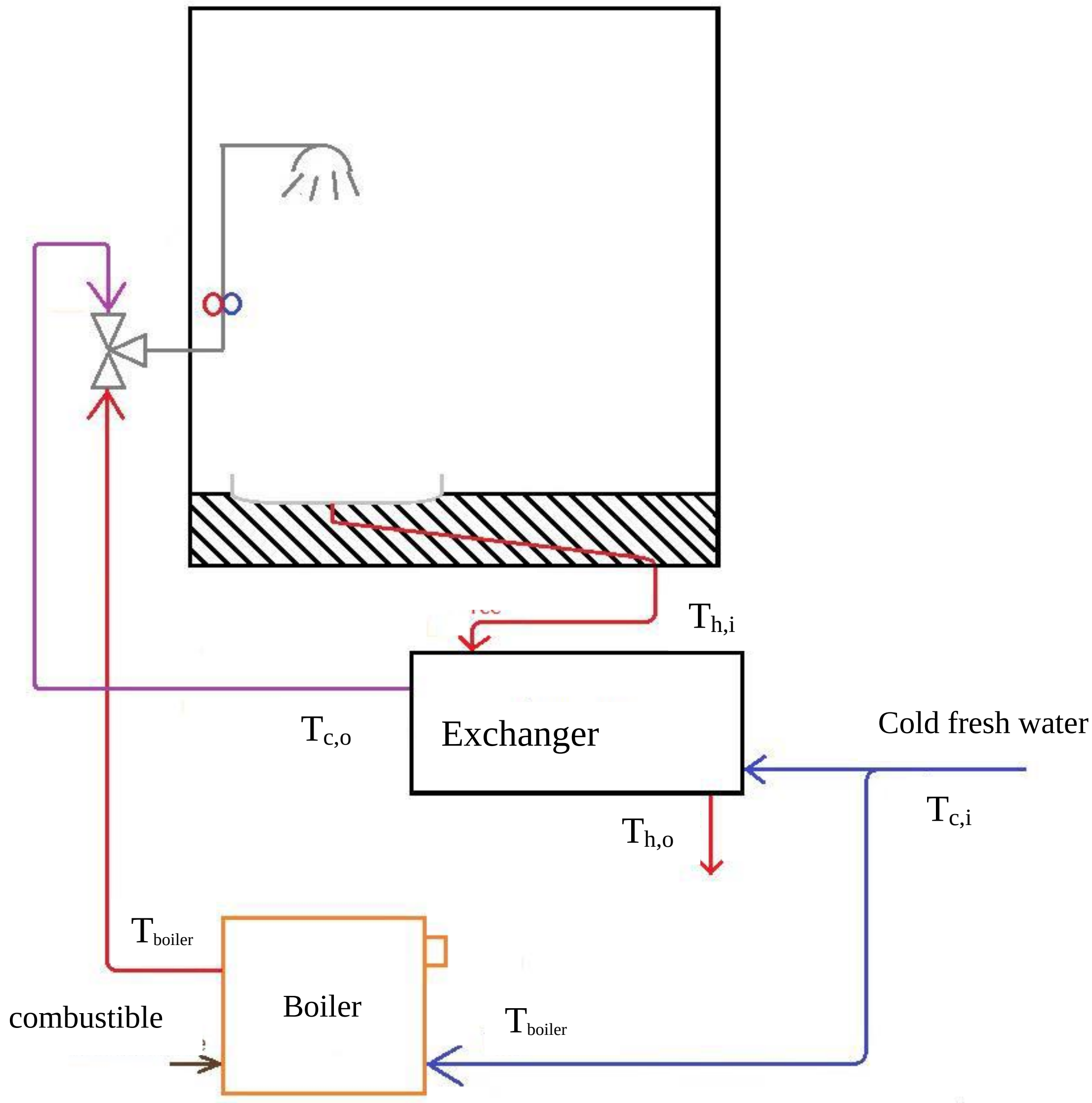


Figure 22.Schematic representation of the first experimental unit.

3.1.1- Heat exchanger

The heat exchanger is a copper pipe (cold fresh water) diameter 10 mm passing through a (PVC) pipe (drain water) 40 mm and counterflow to heat transfer from hot gray water to cold fresh water shown in (figure 23). Simplified diagram of the final installation heat exchanger shown in (figure 24).

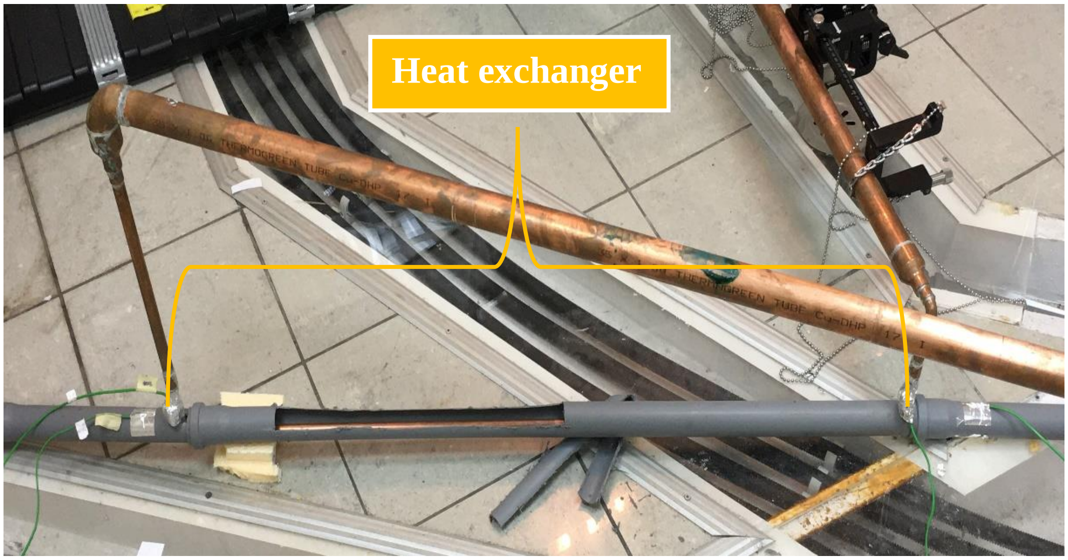


Figure 23. Heat exchange unit.

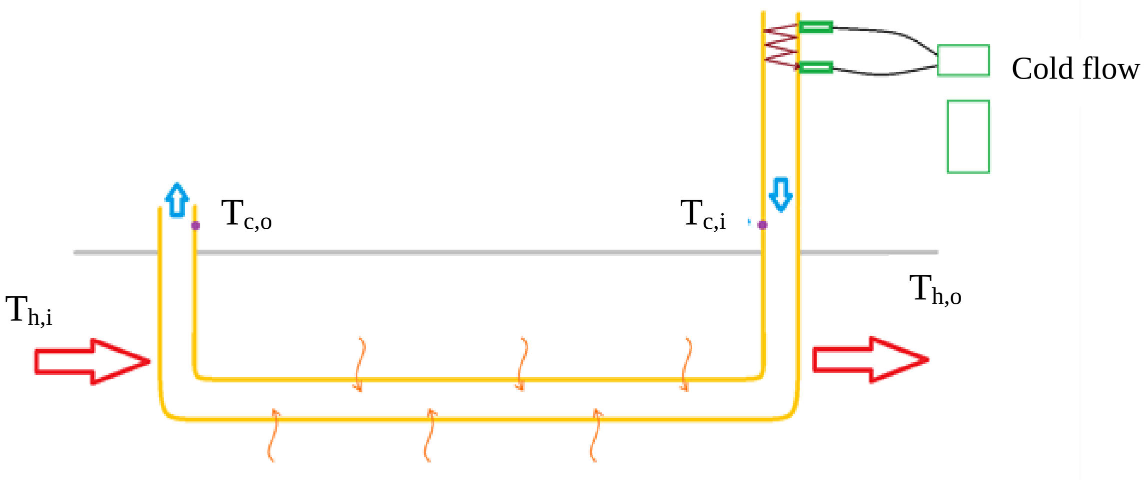


Figure 24.Simplified diagram of the final installation heat exchanger.

3.1.2- Measurement tools

a- Ultrasonic Flow Meter for Liquids

The flow meter shall be tightly fixed on the cold water piped shown in (figure25).

1- Place the transformer in the device with the special gel material between the transformer and the pipe.

2- to connect the special cable that connects the transformers with the transmitter with the choice of the channel.

3- Turn on the transmitter and tablet and go to the application (transport PT 900) that was already downloaded and wait for the Bluetooth lamp to turn from red to blue. Once connected we enter the program menu and select the first or second channel according to the cable connected with the transmitter.

Figure 25.Ultrasonic Flow Meter for Liquids.

b- Thermocouples and data logger(ALMEMO-710)

The thermocouples will remain in the same place throughout the experiment period as follows shown in (figure 26):

1- One, in a small hole made in the drain pipe before the heat exchanger, which measures the temperature of the hot inlet and is symbolized by $T_{h,i}$.

2- One, in a small hole made in the drain pipe after the heat exchanger and symbolized by $T_{h,o}$.

3- The other two shall be on the copper tube for cold water without contact with water. The first is put before the heat exchanger and symbolized by the $T_{c,i}$ symbol and the second is after the heat exchanger and the symbol is $T_{c,o}$.

Figure 26.Thermocouples and data logger.

The data is transmitted by 5 meter wires to the data recorder. This data can then be transferred from the data logger to the computer and the calculations can be performed.

3.1.3- Display data

The data for the experiment is collected on the following:

1- Temperature drain hot water inlet to heat exchanger.
2- Temperature drain hot water outlet from heat exchanger.
3- Temperature cold fresh water inlet heat exchanger.
4- Temperature cold fresh water outlet heat exchanger.
5- Flow rate cold fresh water.

3.1.4- Results

The results in the first experiment showed the maximum discharge obtained from the opening the tap to maximum (Q max =21.45 l/min) and the discharge was reduced compared to maximum discharge where it (80%, 60%, 46%, 26% and 11% from Q max) and recording reading temperature of the cold fresh water and gray water (waste water) to discharge different. Where the temperature readings obtained from the data logger almemo-710 and the flow and mass flow were obtained through the Ultrasonic Flow Meter for Liquids as well as q calculated shown in (table 1).

Table 1. data temperature and flow rate.

	Flow (Q) L/min	**Mass flow** Kg/h kg/Sec	$T_{h,i}$ (C^o)	$T_{h,o}$ (C^o)	$T_{c,i}$ (C^o)	$T_{c,o}$ (C^o)	q (W)
Q_{max}	21.45	1284.44 - 0.36	47.04	47.29	14.60	18.68	6790.39
80% Q_{max}	17.13	1036.79 - 0.29	47.35	44.75	14.93	19.23	5200
46% Q_{max}	9.89	592.05 - 0.16	47.93	45.76	15.10	21.24	4106
26% Q_{max}	5.51	330.66 - 0.09	47.65	46.38	15.83	23.17	2761.31
11% Q_{max}	2.4	143.97 - 0.04	46.80	45.35	16.35	24.58	1376.06

Figure (27) shows the relationship between the total rate of heat transfer and discharge, since increasing discharge leads to an increase in the total rate of heat transfer.

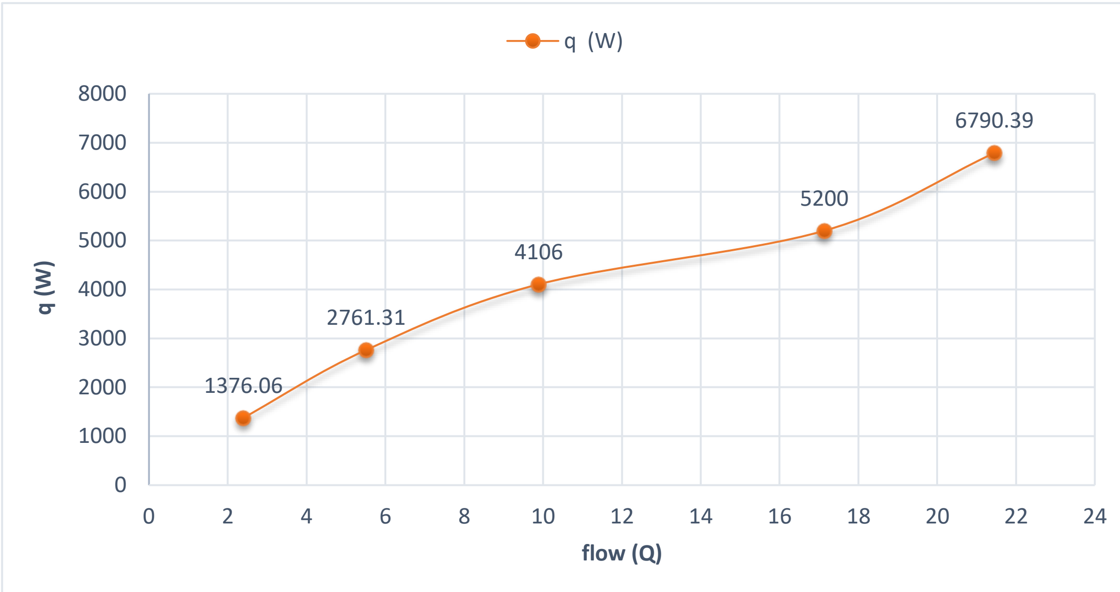


Figure 27.the relationship between the total rate of heat transfer and discharge.

3.2- Final Experimental Setup - Scope, technology, Objectives

The main objective of the final experimental setup is to develop a smart energy efficient demonstrator with an air-water unit and a water-water heat recovery unit integrated in a building wastewater system. Finally this device should be integrated on a horizontal wastewater collector inside buildings. The demonstrator that we are going to develop in the laboratory will have two ways to recover the energy from the wastewater flow; the first way is a water – water interface which will allow the heat recovery via a water flow from the heat wastewater potential and the second one is an air – water interface which allows the heat recovery via an air flow also from the wastewater heat potential. A section of this demonstrator is presented in (figure 28).

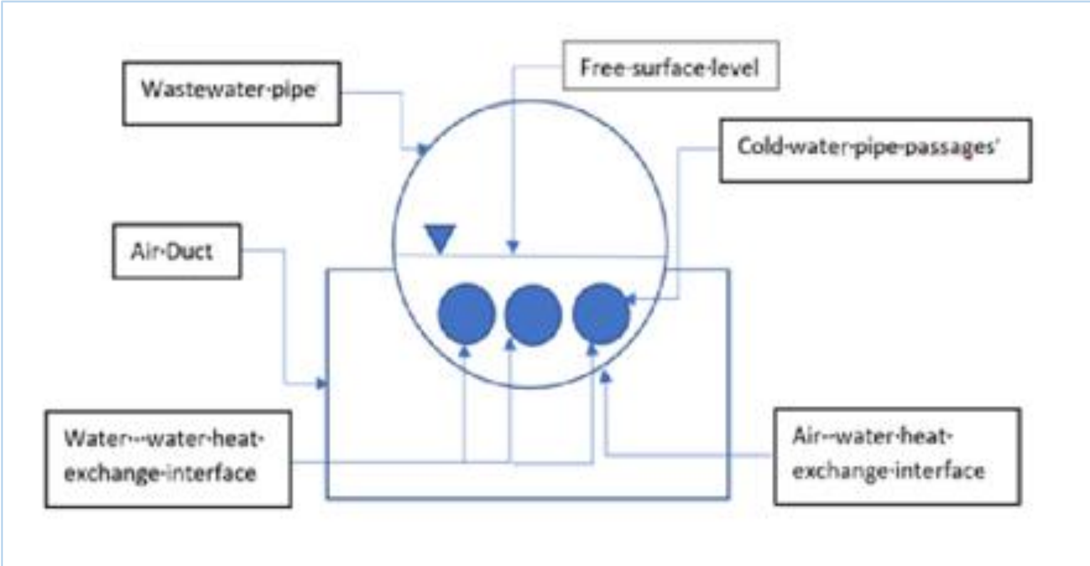


Figure 28.Section of the experimental demonstrator.

Our demonstrator will be dedicated to the usage inside a building to recover the energy only from the grey wastewater and to be used directly to preheat the hot water or indirectly by using a heat pump.

In order to understand the utility of this demonstrator and its degree of novelty in relation to the national and international state of the art it is very important to provide answers to these very simple questions: ***i) why do we need such a device? ii) why did we think to conceive the demonstrator to be used on a horizontal collector wastewater pipe? iii) why did we think to provide two different ways to recover the energy from wastewater and iv) how energy efficient such a device could be?*** We will answer all these questions starting from the preliminary results and from the national and international state of the art related to the subject in order to justify our choices.

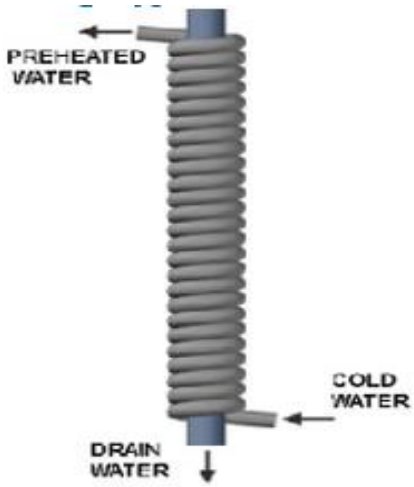
Why do we need such a device? The answer to this first question is very simple: we have to reduce energy consumption and CO2 footprint in existing buildings without major construction work. As already stated many of these buildings represent heritage buildings and the intervention constraints on the original building are much more restrictive for these particular cases. The building sector is one of the world's largest energy consumers, so it is important to seek out and use recovery energies for individual consumers. The main component of energy consumption in buildings is heating, but the demand for the domestic hot water is also very high, especially when daily consumption is high and especially for specific applications (hotels or laundries for example). This is why the implementation of technologies using heat recovery from wastewater has become very important. These goals can be met only by using high performance materials, **cost-effective energy**

efficient systems and systems based on renewable energy sources. **One of the cost-effective energy efficient system could be our heat recovery system from wastewater.** L.Ni et al. [20] proposed a grey water energy recovery system with a multiple function heat pump system. The authors have developed a numerical model for the investigation of the annual energy and water consumptions of the proposed system and the conventional building energy system with gas furnace space heating, package air conditioning and electricity water heater for hot water heating. Based on a case study of a typical residential house with four family members the results show that the proposed system can provide about 33,9% energy savings for space heating, cooling and hot water heating. The study is extended among 15 cities in various climatic zones in the US and the results show energy savings having ranges of 17% - 57.9 %. As a conclusion we may answer the first question by saying that we need such a device to be able to renovate old buildings, especially historical buildings where the intervention on the exterior is very limited.

Why did we think to conceive the demonstrator to be used on a horizontal collector wastewater pipe? Manny studies can be found in the literature regarding the heat recovery from wastewater. Jorgen Wallin & Joachim Claesson [21] have studied the performance of a vertical inline drain water heat recovery heat exchanger. In this case the system recovers the heat with the aid of a heat pump. Investigation of the heat recovery ratio shows that the heat exchanger has the capability to recover more than 25% of the available heat in the drain water at the flow rates investigated.

S. Torras et al [22] investigated also the performance of a vertical drain water heat recovery system as an interesting household technology to reduce energy costs and environmental impact. A specific drain water heat recovery storage-type based on a cylindrical tank with an internal coiled pipe (see figure 29) has been built and both numerical and experimental tools have been used to design and study the performance of the device. The DWHR storage had the capacity

to recover from 34% to 60% of the energy available in the drain water for the investigated flow rates.



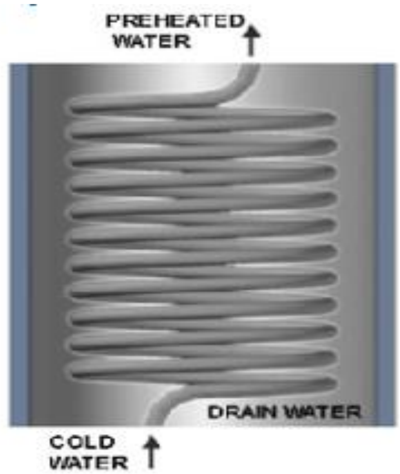


Figure 29. on left on-demand DWHR, on the right storage DWHR.

However, this type of vertical heat exchangers is not easy to use because of the lack of space and the integration of the horizontal heat exchangers could be interesting from this point of view.

L.T. Wong et al. [23] investigated the potential for shower water heat recovery from bathrooms equipped with instantaneous water heaters in high rise residential buildings of Hong Kong. They proposed a single – passed counter flow heat exchanger horizontally used for preheating the cold water before a water heater. The thermal energy exchange is evaluated in terms of effectiveness-number of transfer units approach and the results indicate that 4 to 15% shower water heat could be recovered through a 1.5 m long single pass counter flow heat exchanger for a drainage pipe of 50 mm diameter. Aonghus McNabola and Killian Shields [24] have also pointed out that the recovery of the waste heat from the domestic wastewater flows is a viable method of improving the energy efficiency of buildings. Their study is of great importance for the proposal here, because they have analysed the efficiency of such a heat exchanger.

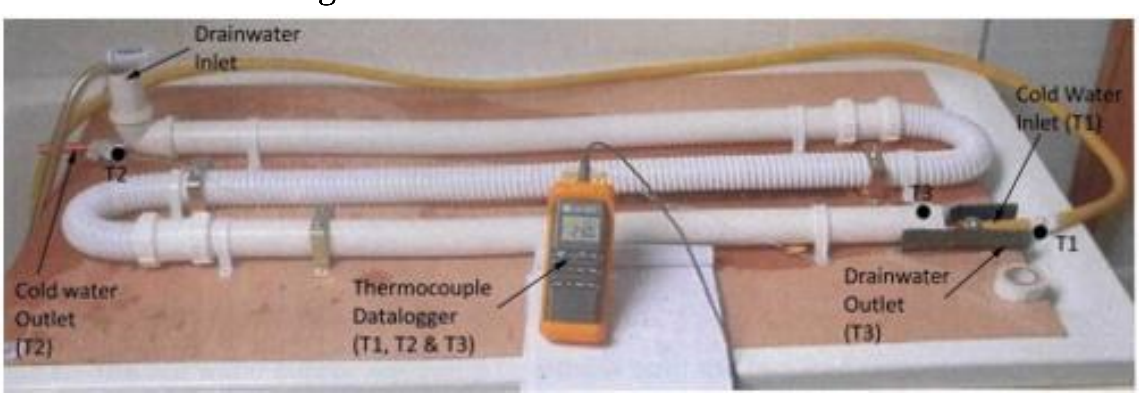


Figure 30.Experimental setup of proposed DWHR unit.

They have proved that even if many of the existing systems only operate satisfactorily when the heat exchanger is in a vertical orientation due to the nature of wastewater flow within the drainpipes, this orientation requirement presents a barrier to the full-scale implementation because of limited space especially in dwellings. The paper outlines the experimental analysis of a horizontal drain water recovery system (see figure 30) for domestic showers and the possibility of increasing the efficiency of such systems. The results also demonstrate that such a system may be economically viable depending on several external factors such as the price of energy, the local climate, the capital cost of the device and the national incentives for energy saving technology. **In this case improving the efficiency of such a heat exchanger could be the solution to make them more usable. Our conclusion is that the efficiency of the heat exchangers may be higher for the vertical ones but the lack of space especially in dwellings suggests that the horizontal ones are more appropriate.** Even the horizontal ones are sometimes hard to install especially in the historical buildings where the intervention constraints on the original building are much more restrictive and this is where our proposal provide the solution to use the horizontal wastewater collectors which already exist inside the building and have their dedicated space as heat exchangers for the recovery of the energy. This solution requires no additional space to be used and can be implemented inside all buildings no matter if there are ordinary buildings or special buildings. **Therefore, we conceived the demonstrator to be used on a horizontal collector wastewater pipe and one of the goals will be to improve its energy efficiency.**

Why did we provide two different ways to recover the energy from wastewater? The answer is very simple, if we use two ways to recover the energy from the wastewater, we increase the efficiency of the device and we recover more heat. The quantity of the heat energy extracted from the wastewater is higher. Another big advantage of this solution is the fact that the" two recovery lines" could work independently one from another depending on the interior/exterior conditions. For example, it is possible that for low air temperatures the energy efficiency of the heat exchanger could be very high on the air heat recovery and the cold water line should be stopped during this period (probably in winter time) while the efficiency could be more important on the water line during summer time when the air temperature is high. The scenario applied to the behaviour of the demonstrator will be managed by a smart system using sensors to monitor mainly temperatures and flowrates. **The solution is innovative because there are no heat exchangers**

implemented on the wastewater pipes providing two ways to recover heat, a water line and an air line.

How energy efficient such a device could be? We have already red in the state of the art that the energy efficiency of the horizontal wastewater heat exchanger could be improved. There are lot of classical methods to improve the heat transfer through an interface inside a heat exchanger. For example S. Liu and M. Sakr[25] provide a very detailed state of the art. The passive method generally uses surface or geometrical modifications to the flow channel by incorporating inserts or additional devices, for example, inserts extra component, swirl flow devices, treated surface, extended surface, displaced enhancement devices, coiled tubes, surface tension devices and additives for fluids. There are also active methods to improve the heat transfer such as the use of magnetic fields, surface vibration, fluid vibration, electrostatic fields or impinging jets which require an external activator/power supply to bring about the enhancement. The two cited categories could be used in combinations such us rough surface with a twisted tape swirl flow device, or rough surface with fluid vibration, or rough surface with twisted tapes. The heat transfer interface optimisation for our demonstrator will focus on the passive methods. For the convective heat transfer, one of the ways to enhance heat transfer rate is to increase the effective surface area and residence time of the heat transfer fluids. The passive methods are based on these principles by employing several techniques to generate the swirl in the bulk of the fluids and disturb the actual boundary layer to increase effective surface area, residence time and consequently heat transfer coefficient in existing system. Although there are hundreds of passive methods to enhance the heat transfer performance, we will focus on the following ones for our demonstrator: ***i) rough surfaces***: they are generally surface modifications that promote turbulence in the flow field, primarily in single phase flows and do not increase the heat transfer surface area; ***ii) extended surfaces***: they provide effective heat transfer enlargement; the newer developments have led to modified fin surfaces that also tend to improve the heat transfer coefficient by disturbing the flow field in addition to increasing the surface area; ***iii) displaced enhancement devices:*** these are the insert techniques that are used primarily in confined force convection. These devices improve the energy transfer indirectly at the heat exchange surface by displacing the fluid from the heated or cooled surface of the duct/pipe with bulk fluid to the core flow. The characterization of the heat exchange properties for this kind of interfaces will be done using non-intrusive methods as PIV measurements techniques. We have already performed (Nastase, Sandu et al [26]) PIV experimental studies regarding the flow pattern over rough surfaces in open channel with applicability to the turbulence increasing methods that can be used to enhance the heat flux over an interface.

All these methods are classical and have been applied to classical heat exchangers but no one of them have been yet applied to a wastewater double heat exchange interface on a wastewater pipe.

We can summarize now by saying that our demonstrator finds its utility in a very actual energy efficiency domain and prove its innovative character by the following:

- **smooth integration in a building wastewater system;**
- **double heat recovery possibility for air and for water at high energy efficiency level;**
- **heat exchange interfaces specifically adapted for this application**
- **smart system to monitor and to operate the device in term of temperatures and flowrates to achieve maximum energy efficiency.**

The main objective of this study is to develop a smart energy efficient demonstrator with an air-water interface and a water-water heat recovery interface integrated in a building wastewater system.

The specific objectives are:

OS1: Development of a water -water heat exchange interface allowing a high-rate heat flux from the wastewater flow to the cold-water flow;

OS2: Development of an air – water heat exchange interface allowing a high-rate heat flux from the wastewater flow to the airflow.

OS3: Integration of the demonstrator two heat recovery systems into a smart system to monitor and to control the energy loads. The goal of this specific objective is to provide a good practice guide for the experimental demonstrator in terms of air/water flowrates and temperatures in order to increase the energy savings.

Reference

1. Burlacu, A., et al., *Energy efficient heat pipe heat exchanger for waste heat recovery in buildings*, in *11th International Conference Interdisciplinarity in Engineering, Inter-Eng 2017*, L. Moldovan and A. Gligor, Editors. 2018, Elsevier Science Bv: Amsterdam. p. 714-721.
2. Bertrand, A., R. Aggoune, and F. Marechal, *In-building waste water heat recovery: An urban-scale method for the characterisation of water streams and the assessment of energy savings and costs.* Applied Energy, 2017. **192**: p. 110-125.
3. Cipolla, S.S. and M. Maglionico, *Heat recovery from urban wastewater: analysis of the variability of flow rate and temperature in the sewer of Bologna, Italy*, in *Ati 2013 - 68th Conference of the Italian Thermal Machines Engineering Association*, G.L. Morini, et al., Editors. 2014, Elsevier Science Bv: Amsterdam. p. 288-297.
4. Somogyi, V., V. Sebestyen, and E. Domokos, *Assessment of wastewater heat potential for district heating in Hungary*. Energy, 2018. **163**: p. 712-721.
5. Todorovic, M.S. and J.T. Kim, *In search for sustainable globally cost-effective energy efficient building solar system - Heat recovery assisted building integrated PV powered heat pump for air-conditioning, water heating and water saving*. Energy and Buildings, 2014. **85**: p. 346-355.
6. Wang, Y.M., et al., *Comparison and Analysis of Heat Transfer Enhancement for Wastewater Heat Exchanger in Wastewater Source Heat Pump System*, in *10th International Symposium on Heating, Ventilation and Air Conditioning, Ishvac2017*, P. Cui, J. Liu, and W. Zhang, Editors. 2017, Elsevier Science Bv: Amsterdam. p. 2736-2743.
7. Culha, O., et al., *Heat exchanger applications in wastewater source heat pumps for buildings: A key review*. Energy and Buildings, 2015. **104**: p. 215-232.
8. Young, D.F., T. Okiishi, and W. Huebsch, *Fundamentals of fluid mechanics*. 2006: Wiley.
9. Modi, P. and S. Seth, *Hydraulics and Fluid Mechanics: Including Hydraulic Machines (in SI Units)*. 2011: Standard Book House.
10. Rouse, H., *Laboratory instruction in the mechanics of fluids*. 1961.
11. Rajita, G. and N. Mandal. *Review on transit time ultrasonic flowmeter*. in *2016 2nd International Conference on Control, Instrumentation, Energy & Communication (CIEC)*. 2016. IEEE.
12. company, g.e.,

Transport® PT900 Portable Ultrasonic Flow Meter for Liquids. february 2017.
13. GmbH, A.M.-u.R., *Data logger ALMEMO® 710 for all sensors*.
14. Wu, j., *A Basic Guide to Thermocouple Measurements*. 2018: TexasInstrumentsIncorporated. p. 1-37.
15. Keane, R., R. Adrian, and Y. Zhang, *Super-resolution particle imaging velocimetry*. Measurement Science and Technology, 1995. **6**(6): p. 754.
16. Raffel, M., C. Willert, and J. Kompenhans, *Particle Image Velocimetry: A Practical Guide Springer Verlag*. Berlin, Heidelberg, 1998.
17. dantic dynamics, n.i.c., *FLOW FIELD DIAGNOSTICSParticle Image Velocimetry solutions*.
18. Eder, A., B. Durst, and M. Jordan, *Laser-Doppler Velocimetry—Principle and Application to Turbulence Measurements*, in *Optical Measurements*. 2001, Springer. p. 117-138.
19. Jordan, M., *Zündung und Verbrennung in vorgemischten turbulenten Freistrahlen*. 1999: na.
20. Ni, L., et al., *Feasibility study of a localized residential grey water energy-recovery system.* Applied Thermal Engineering, 2012. **39**: p. 53-62.
21. Wallin, J. and J. Claesson, *Investigating the efficiency of a vertical inline drain water heat recovery heat exchanger in a system boosted with a heat pump*. Energy and Buildings, 2014. **80**: p. 7-16.
22. Torras, S., et al., *Drain water heat recovery storage-type unit for residential housing.* Applied Thermal Engineering, 2016. **103**: p. 670-683.
23. Wong, L.T., K.W. Mui, and Y. Guan, *Shower water heat recovery in high-rise residential buildings of Hong Kong.* Applied Energy, 2010. **87**(2): p. 703-709.
24. McNabola, A. and K. Shields, *Efficient drain water heat recovery in horizontal domestic shower drains*. Energy and Buildings, 2013. **59**: p. 44-49.
25. Liu, S. and M. Sakr, *A comprehensive review on passive heat transfer enhancements in pipe exchangers*. Renewable & Sustainable Energy Reviews, 2013. **19**: p. 64-81.
26. Iliescu, M., et al., *An Experimental Approach Regarding the Sewage Self-Cleansing Conditions*, in *Eenviro-Yrc 2015 - Bucharest*, R.M. Damian, Editor. 2016, Elsevier Science Bv: Amsterdam. p. 266-272.