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# THERMAL INSULATION OF HOT WATER PIPES IN THE ANNEX RESIDENCE

Authman Abdali et Anas Bentamy,
*School of Science and Engineering, Al Akhawayn University*
*P.O Box 104, Hassan II Avenue, 53000 Ifrane, Morocco*
***au.abdali@gmail.com& a.bentamy@aui.ma***

**Abstract :**

Hot water is an important feature in daily life. Dishwashing, hand-washing, bathing, and laundry are all applications where human beings use hot water. As a result, water heating became one of the processes that contribute significantly in water and energy wastes. This paper investigates the potential heat losses that occur in a non-insulated hot water pipe while pumping the fluid from the boiler to the fixture where it is used. Heat losses occur by convection in the internal flow of water inside the pipes and conduction through the pipe thickness itself. Insulation plays a crucial role in reducing heat losses in hot water pipes since the insulating layer increases the thermal resistance of the whole system. The objective is to estimate the reduction of heat losses by choosing an appropriate insulating material available in the Moroccan market. The results show that hot water pipes insulation is an efficient and effective way to reduce energy and water losses.

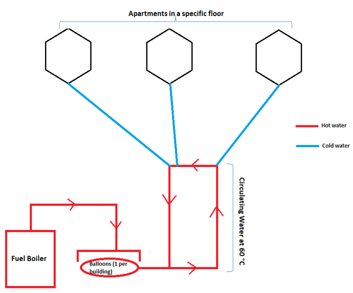
**Keywords**: convection, conduction, thermal insulation.

## 1. Introduction

The main problem encountered during the process of water heating is not only the huge amount of energy needed to heat water initially, but also the time taken by hot water to reach the tap; a considerable volume of cold water is lost in order to get hot water. As a matter of fact, when one closes the hot water tap, hot water remains in the pipes connecting the furnace to the tap, and with time, that water loses heat to the surrounding environment and turns cold. The next time one opens the hot water tap, the cold water remaining in the pipes goes out first and is automatically wasted before hot water reaches the tap. The purpose of this study is to find a way to minimize water losses and energy. Hot water needs time to get to the tap because the bad thermal insulation results in considerable heat losses while piping hot water. Accordingly, the problem is twofold: cold water remaining in the pipes, and more importantly, the bad thermal insulation that makes hot water loses some of its heat to the surroundings, which increases the needed time for hot water to reach the taps.

## 2. Description of the existing system.

The core of the water heating system existing in the Annex Residence at Al Akhawayn University is in the basement. There is a fuel boiler (figures 1&2) that burns fuel in order to heat water initially; its power ranges from 120 KW to 650 KW. Once the water is heated, it goes through some channels to a sort of tanks equipped with a heat exchanger. Since there are six buildings, there are six tanks; one per building. These tanks store hot water for sanitary use. Since these tanks are linked to the boiler, they contain permanently hot water at 60 °C, and heat exchangers enable the heat transfer between the cold and hot water inlets. For every single building, re-circulated hot water reaches each floor, and then there are branches that link that closed path of hot water to each apartment. These branches aren't permanently hot since warm water is not circulated there. Accordingly, our main problem arises: these branches aren't well insulated which causes a huge loss of water once being cold.




Figures 1& 2: Fuel boiler used in the Annex Residence & Current water heating system.

## 3. Temperature and water waste measurements.

Several apartments in the Annex Residence have served to measure the time it takes for hot water to reach the taps, and also the volume of cold water that is lost during this process. It has been noticed that hot water never reaches the 60 °C as in re-circulation part even after a really long time. On average, the exit temperature was around 45 °C, and the total lost volume of water was around 40 liters. Those measurements were conducted using average water flow rate of 0.16 l/s. The volume of water that is trapped in the pipes constitute only 25% of the total lost volume of water, which implies that 75% of water losses are due to bad thermal insulation!

## 4. Analysis of the current heat loss in the steady phase.

For the calculations, the heat loss is quantified in one apartment under steady flow assumptions, and then the heat loss per unit of length of the pipe is extracted. Steady flow state is defined as the phase during which the exit temperature is stabilized. The total heat loss for all the apartments is deduced since the piping system is under the same conditions.

### 4.1. Inner convection coefficient calculation

The first step is to calculate Reynolds Number in order to determine the nature of the flow. The thermo-physical properties of water at the mean temperature are used. The mean temperature is the average temperature between the inlet of the pipe (the one leaving the re-circulating loop), and the outlet of the pipe:

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2} = \frac{60+45}{2} = 52.5°C (1)$$

The Reynolds number is then

$$\mathrm{Re} = \frac{\mathbf{V} * D_i}{\upsilon} = \frac{0.51 * 0.02}{5.326 \times 10^{-7}} = 19151.33 \ (2)$$

Since Re > 10000, the flow is fully turbulent. Since 0.7 < Pr = 3.4 < 160, the Nusselt number is determined via

the Colburn equation [1] from which the he inner convection heat transfer coefficient is obtained:

$$Nu = \frac{hD_i}{k} = 0.023 * \mathrm{Re}^{0.8} * \mathrm{Pr}^{0.3} = 0.023 * 19151.33^{0.8} * 3.4^{0.3} \cong 88.5 \ (3)$$

$$h_i = \frac{k}{D_i} Nu = \frac{0.6465 \ \mathrm{W/m.°C}}{0.02 \ \mathrm{m}} (88.5) = 2860.76 \ \mathrm{W/m^2.°C} \ (4)$$

### 4.2. Surface temperature calculation.

The inner surface area is:

$$A_{s,i} = \pi D_i L = \pi (0.02\mathrm{m})(32.3 \ \mathrm{m}) = 2.03 \ \mathrm{m}^2 (5)$$

A constant surface temperature along the pipe is assumed. To estimate the inner surface temperature, considering

a constant surface temperature, and integrating between the tube inlet and outlet we get the following equation:

$$\ln \frac{T_{s,i} - T_e}{T_{s,i} - T_i} = -\frac{h_i * A_{s,i}}{\dot{m} * c_p} (6)$$

This equation is solved for $T_{s,i}$:

$$T_{s,i} = \frac{T_e - T_i * e\left(-\frac{h_i * A_{s,i}}{\dot{m} * c_p}\right)}{1 - e\left(-\frac{h_i * A_{s,i}}{\dot{m} * c_p}\right)} = \frac{45 - 60 * e\left(-\frac{2860.7625 * 2.03}{986.65 * 0.16 * 10^{-3} * 4182}\right)}{1 - e\left(-\frac{2860.7625 * 2.03}{986.65 * 0.16 * 10^{-3} * 4182}\right)} \cong 45°C (7)$$

This result shows that the fluid temperature tends at the end to the inner surface temperature.

### 4.3. Outer convection coefficient.

Outside the pipe, the natural convection coefficient of still air is computed. The air properties at the film temperature are used:

$$T_{film} = \frac{T_{s,o} + T_{ambient}}{2} = \frac{20+45}{2} = 32.5°C \quad (8)$$

Empirical correlations for the average Nusselt number for natural convection over horizontal cylinder [2] are used:

$$Nu = \left\{ 0.6 + \frac{0.387 * Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.559}{\Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2 = 5.39 \quad (9)$$

The Rayleigh number Ra is the product of the Grashof number for cylindrical pipe and the Prandtl number:

$$Ra = Gr * \Pr = 32113.8 * 0.7275 = 23362.8 \quad (10)$$

with the volumetric thermal expansion coefficient β and the Grashof number equal respectively:

$$\beta = 1/(32.5+273) = 0.003273322 \text{ (1/K)}$$

$$Gr = \frac{g\beta(T_{s,o} - T_{\infty})D_o^3}{\upsilon^2} = 32113.8 \quad (11)$$

The outer convection coefficient $h_o$ is obtained from the average Nusselt number hence computed:

$$h_o = \frac{k * Nu}{D_o} = \frac{0.026065 * 6.38}{0.022} = 6.38 W/m^2.°C \quad (12)$$

### 4.4. Total thermal resistance of the non-insulated hot water pipe system.

The thermal resistance network of the hot water pipe system is shown on Figure 3.


Figure 3: In series resistances in the un-insulated pipe.

The total resistance is simply:

$$R_i = R_{conv,1} = \frac{1}{h_{in} * 2 * Pi * r_1 * L}; R_1 = R_{pipe} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 * Pi * k_{pipe} * L}; R_o = R_{conv,2} = \frac{1}{h_{out} * 2 * Pi * r_2 * L} \quad (13)$$

$$R_{total} = R_i + R_1 + R_o$$

$$R_i = \frac{1}{h_i * pi * D_i * L} = \frac{1}{2860.7625 * pi * 0.02 * 32.3} = 0.000172 °C/W \quad (14)$$

$$R_{pipe} = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2 * pi * L * k_{pipe}} = \frac{\ln\left(\frac{0.022/2}{0.02/2}\right)}{2 * pi * 32.3 * 48} = 9.78894 * 10^{-6} °C/W \quad (15)$$

$$R_o = \frac{1}{h_o * pi * D_o * L} = \frac{1}{6.38 * pi * 0.022 * 32.3} = 0.07021849 °C/W \quad (16)$$

$$R_{total} = R_i + R_{pipe} + R_o = 0.000172 + 9.78894 * 10^{-6} + 0.07021849 = 0.0704 °C/W \quad (17)$$

The thermal resistances of the conduction through the bare pipe and the inner convection are too small compared to the outer convection resistance. They can be neglected without causing any significant errors (result used in the insulation part).

#### 4.4. Rate of heat loss.

The rate of heat loss is:

$$\dot{Q} = \frac{T_{ambient} - T_{fluid,mean}}{R_{total}} = \frac{20 - 52.5}{0.0704} = \text{-461.64W} \ (18)$$

Ignoring the thermal resistances of conduction through the bare pipe and inner convection, a rate of heat loss of -462.84 W is found, which corresponds to only 0.26% of difference.
Accordingly, the rate of heat loss per unit length (meter) is:

$$\dot{Q}_{/meter} = \frac{\dot{Q}}{L} = \frac{-461.64}{32.3} = \text{-14.3W/m} \ (19)$$

#### 4.4. Surface temperature drop.

The temperature drop across the pipe is then:

$$\Delta T_{pipe} = \dot{Q} * R_{pipe} = -461.64 * 9.78894 * 10^{-6} = \text{-0.004519°C} \ (20)$$

One can notice that the temperature between the inner and outer surface of the pipe vary by only 0.004519°C, which almost zero. The pipe is isothermal, which means that the inner and outer surface temperatures are the almost the same (45°C) which confirms that the heat transfer is mainly caused by outer convection.

#### 4.4. Heat losses for the whole residence.

With the plans of the Annex Residence of Al Akhawayn University, the length of the pipes coming into all the apartments is 1763.1 m.
Using the rate heat loss per unit length obtained earlier:

$$\dot{Q}_{total} = \dot{Q}_{/meter} * L_{total} = -14.3 * 1763.1 = \text{-25198.9W} = \text{-25.2}kW \ (21)$$

#### 4.5. Calculation of the current cool down time.

An estimate of how quickly hot water cools down in the pipes after closing the taps is given by Newton's law of cooling [1]:

$$T(t) = T_{surrounding} + (T_{hot} - T_{surrounding}) * e^{\left(\frac{-1}{m * c_p * R_{total}}\right)t} \ (22)$$

By neglecting both inner convection and conduction through the bare pipe:

$$T(t) = 20 + (52.5 - 20) * e^{\left(\frac{-1}{10.01 * 4182 * 0.0702}\right)t} \ (23)$$

Assuming a minimum useful warm temperature of 30°C, the water reaches it in approximately 3500 sec (58 minutes). Users have only 58 minutes between hot water draws in order to not wait and loose water.

## 5. Insulation analysis.

To measure the heat transfer within an insulated pipe, resistances in series similar to the un-insulated case are computed added with the resistance of the insulation layer. Figure 4 shows the new cross section and figure 5 shows the corresponding thermal resistances network.

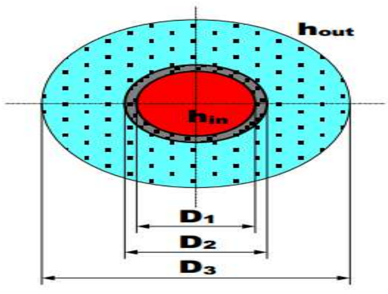



Figure 4: Cross section of an insulated pipe.

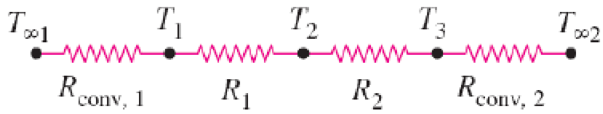


Figure 5: In series resistances in an insulated pipe.

The different thermal resistances are then:

$$R_i = R_{conv,1} = \frac{1}{h_{in} * 2 * Pi * r_1 * L}; R_1 = R_{pipe} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 * Pi * k_{pipe} * L}; R_2 = R_{insulation} = \frac{\ln\left(\frac{r_3}{r_2}\right)}{2 * Pi * k_{insulation} * L}; R_o = R_{conv,2} = \frac{1}{h_{out} * 2 * Pi * r_3 * L} (24)$$

The total thermal resistance is then: $R_{total} = R_i + R_1 + R_2 + R_o$

**5.1. Insulation thickness calculations.**

The calculation of the insulation layer thickness depends on a given mean bulk temperature of water and a desirable outside temperature. An approximate outside surface temperature of 27 °C and a thickness of 1.5 cm are found after doing several simulations for different insulation layers using the software TechCalc (version 1.0.2.7). The choice for the insulation material is fiberglass due to the facts [3, 4]:
- Fiberglass is very cheap compared to other insulation materials used in pipe insulation (like mineal wool or spray foam),
- Flexibility in terms of installation (easy to install),
- Environment friendly since it is composed of 70% recycled glass,
- High fire resistance (not combustible),
- High water resistance (recovers all its properties after drying if there was any contact with water),
- Does not shrink or expand with heat (dimensionally stable),
- Resistance to insects (not easily damaged),
- Low thermal conductivity (0.04 W/m.K),
- High chemical resistance,
- High tensile strength,
- Low moisture absorption,

As previously shown, the inner convection and pipe conduction thermal resistances can be omitted, only the outer convection and insulation conduction thermal resistances are considered. Once a thickness of insulation and a desired percentage of reduction in the rate of heat loss are chosen, the values of the thermal resistances are computed from which the exit temperature of the pipe is obtained. The calculation is based here again on the shower of apartment 6 in building 7.
Using the surface temperature of 27°C, the thermo-physical properties of still air at film temperature are:

$$T_{film} = \frac{T_{ambient} + T_{surface}}{2} = 23.5°C (25)$$

To determine the natural convection coefficient, we use the same method as in the previous case. The volumetric thermal expansion coefficient is: *β = 1/ (23.5+273) = 0.00337268* (1/K) from which the Grashof number is obtained:

$$Gr = \frac{g\beta(T_{s,o} - T_\infty)D_o^3}{\upsilon^2} = 135862.0785 \; (26)$$

The Rayleigh number is then:

$$Ra = Gr * \Pr = 135862.0785 * 0.729999 = 99177.95867 \; (27)$$

and the Nusselt number:

$$Nu = \left\{ 0.6 + \frac{0.387 * Ra^{\frac{1}{6}}}{\left[ 1 + \left( \frac{0.559}{\Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right\}^2 = 7.79 \; (28)$$

Finally, the outer convection is found to be:

$$h_o = \frac{k * Nu}{D_o} = \frac{0.025399 * 7.79}{0.052} = 3.8 W / m^2.°C (29)$$

The natural convection thermal resistance becomes:

$$R_o = \frac{1}{h_o * pi * D_o * L} = \frac{1}{3.8 * pi * 0.052 * 32.3} = 0.049851426 \; W / m^2.°C \quad (30)$$

The thermal resistance of the insulation layer is:

$$R_{insulation} = \frac{\ln\left(\frac{r_3}{r_2}\right)}{2 * pi * L * k_{insulation}} = \frac{\ln\left(\frac{0.052/2}{0.022/2}\right)}{2 * pi * 32.3 * 0.04} = 0.106017588 °C/W \quad (31)$$

Finally, the total thermal resistance is:

$$R_{total} = R_{insulation} + R_o = 0.106017588 + 0.049851426 = 0.155869014 °C/W \quad (32)$$

Knowing that the rate of heat loss from the non-insulated pipe is -461.64 W, so for a 50% reduction, the heat loss from the insulated pipe should be:

$$\dot{Q}_{insulated} = \%reduction * \dot{Q}_{non-insulated} = 0.5 * (-461.64) = -230.82 W \quad (33)$$

This condition leads to the exit temperature:

$$\dot{Q}_{insulated} = \frac{T_{ambient} - T_{fluid}}{R_{total}}$$

$$T_{fluid} = T_{ambient} - (R_{total} * \dot{Q}_{insulated})$$

$$\frac{T_{inlet} + T_{exit}}{2} = T_{ambient} - (R_{total} * \dot{Q}_{insulated})$$

$$T_{exit} = 2 * (T_{ambient} - (R_{total} * \dot{Q}_{insulated}) - T_{inlet}$$

$$T_{exit} \approx 52°C \quad (34)$$

For a 1.5 cm thickness of fiberglass insulation, a 50% reduction in the rate of heat loss leads to an exit temperature of 52°C. Hence energy is saved by decreasing the rate of heat loss, but also hotter water is obtained at the fixture.

**5.2. Calculations of the cool down time after insulation.**

The Newton law of cooling is used here again and is illustrated on the following graph (figure 6):

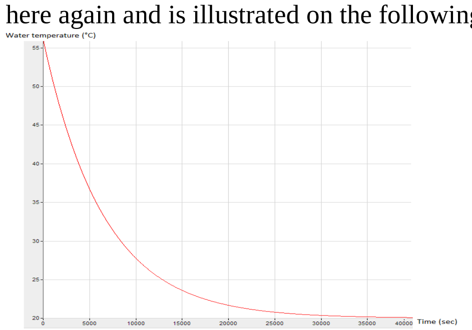



Figure 6: Cool down curve for the current system.

Assuming a minimum useful warm temperature of 30°C, one can see water reaches it in approximately 8500 sec (142 minutes). In other words, users have 142 minutes between hot water draws in order to not wait and loose water. If one compares this value to the previous one (67 minutes), he can see that the allowed time between draws has approximately doubled, which means that users have more flexibility and more importantly, water waste will be reduced.

## 5. Cost of insulation.

An average price of 50 MAD/Kg of fiberglass has been found. To compute the cost, the required volume and mass of fiberglass needed to insulate our pipes are needed. The volume is found with:

$$Volume = \pi * L * (r_o{}^2 - r_i{}^2) = 3.07 m^3 (35)$$

Since the density of fiberglass is 0.032 g/cm$^3$, the needed mass is then:

$$Mass = Density * Volume = 98.37 \text{ Kg} \ (36)$$

From these previous calculations, the purchase price is then:

$$\Pr ice = 50 * 138.24 \approx 4920\, MAD (37)$$

For the installation costs, one cannot determine them in advance because they depend on the number of needed workers and their daily salary. Also, the shipping cost depends on the chosen company and many other factors. Accordingly, this study uses only the purchase cost as reference.

## 6. Energy savings.

A similar study has been conducted in Victoria, Australia [5]. An approximate water consumption for hot water is extracted for medium apartments: the daily hot water needs are around 200 liters for all occupants (for an average of 2.5 persons per apartment), and using all the fixtures of the apartment (shower, kitchen, etc.). From this result, the daily needs of the residence in hot water are: 200*64 = 12,800 liters. One can then easily estimate the time needed to heat this amount of water. According the gathered documentation from the ground and maintenance department of Al Akhawayn University, the fuel boiler has a useful power of 600 kW, which means that:

$$Pu \times \Delta t = m \times c_p \times \Delta T$$

$$\Delta t = \frac{992.3 \times 12.8 \times 4.179 \times 40}{600} = 3538.62 \sec \ (38)$$

Knowing that the volume flow rate of fuel through the boiler is the useful power divided by the calorific value of one liter of fuel, we have:

$$\dot{V}_{fuel} = \frac{600}{33.2 \times 10^3} = 0.018 l / s (39)$$

Accordingly, the amount of fuel needed is: 0.018*3538.62 = 63.7 liters/day. Considering the heat losses through the pipes un-insulated only, it represents a percentage of the useful power of the boiler: (25.2/600)*100 = 4%. With the proposed insulation, the heat loss is reduced by 50%, which corresponds to only 0.5*(25.2/600)*100 = 2%. It is equivalent to a daily savings of: 0.02*63.7 = 1.274 liters. As a result, the yearly fuel savings are about: 1.274*365 = 465.01 liters.

The savings calculated before concern only energy; however, after applying insulation, other savings will occur. First, the time needed for hot water to reach the fixture will decrease since the total thermal resistance increased. Like in the steady regime, heat loss during the unsteady regime, which occurs at the beginning, will decrease, so hot water will get faster to the fixture. Accordingly, the volume of water that goes down the drain will decrease significantly.

## Conclusion

In a nutshell, hot water pipes insulation is an efficient and effective way to reduce energy and water losses. In this study, the rate of heat loss in the current system is estimated, and it is tried to minimize it using fiberglass insulation. The main advantages are the extension of the cool down time for hot water trapped in the pipes after each use, which means that the interval between two successive draws has been extended, giving the user more time to benefit from that hot water. In addition, the energy waste that occurs during the pipes' operation is reduced. For water and time wastes, it has been established that the waiting time for hot water decreases significantly along with the amount of water that goes directly down the drain. Finally, it appears that applying fiberglass insulation is very cheap and doesn't require any special skills or funds.

## Acknowledgment

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Residences Manager from Housing Department for his assistance in the temperature measurements and for getting us the permissions to enter the apartments.

**Nomenclature**

Symbols Name, *unit*

**$A_{s,i}$** surface area, m
**$c_p$** specific heat, J/kg.K
**$D_i$** inside cylindrical pipe diameter, m
**$D_o$** outside cylindrical pipe diameter, m
**g** gravity acceleration, $m/s^2$
Gr Grashof number, -
**$h_i$** convection heat transfer coefficient, W/m.°C
**$h_o$** convection heat transfer coefficient, W/m.°C
**k** thermal conductivity, *W/*m.K
**L** length, m
**$m^*$** mass flow rate, kg/s
**Nu** Nusselt number, -
**$P_u$** useful power, W
**Pr** Prandtl number, -
**$r_1$** inner radius of the pipe, m
**$r_2$** outer radius of the pipe, m
**$R_i$** thermal resistance for inner convection, °C/W
**$R_1$** thermal resistance for the conduction through the galvanized steel pipe, °C/W
**$R_2$** thermal resistance for the insulation layer, °C/W
**$R_o$** thermal resistance for outer convection, °C/W
**$R_{tot}$** total thermal resistance, °C/W
**$R_a$** Rayleigh number, -
**$R_e$** Reynolds number, -
**$T_{1-2-3}$** surface temperatures at the different intersections between layers, °C or K
**$T_{s,i}$** inner surface pipe temperature, K or °C
**$T_{s,o}$** outer surface pipe temperature, K or °C
**$T_f$** film temperature, K or °C
**$T_{fluid\ mean}$** average temperature of the fluid, K or °C
**$T_{hot}$** mean bulk temperature of hot water, K or °C
**$T_i$** inlet temperature, K or °C
**$T_e$** exit temperature, K or °C
**$T_\infty$- $T_{surrounding}$** ambient temperature, K or °C
**V*** volume flow rate, $m^3/s$
**V** average velocity, m/s

Greek symbols
**α** thermal diffusivity, $m^2.s^{-1}$
**υ** kinematic viscosity, $m^2.s^{-1}$
**β** thermal expansion coefficient, 1/K
∞ ambient, -

Exponent, Indices
**i** inner
**e** exit or outlet
**o** outer

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