ENERGY AND EXERGY ANALYSIS OF HOT WATER DISTRIBUTION NETWORKS

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In the present paper, energy and exergy losses corresponding to a hot water distribution pipeline were evaluated. For this purpose, mathematical models and computational programs were proposed. To improve the accuracy of the numerical results the effect of friction on the temperature drop was considered. The analysis of the influence of the inlet water temperature and of the mass flow rate was developed and conclusions regarding the operational conditions in district heating networks were formulated.

Keywords: Energy losses, exergy losses, hot water network.

1. Introduction

According to the Kyoto Protocol, the countries energy policy requires reorientation to the international cooperation for sustainable development on a global level. One of the methods is to improve the energy efficiency of the existing systems through optimization of the combined heat and power generation and of the heating networks used for distribution media [1].

For urban area, looking at the energetic efficiency and environmental protection, the centralized hot water systems are the best in heating and preparation of the domestic hot water. The experience of the European developed countries proved that these systems, well made and used, provide the thermal energy needs with the same or even smaller price that offered by the alternative individual solutions, giving multiple advantages. In the EU the number of these systems is growing.

In Romania, there are 144 district heating suppliers that provide thermal energy for almost 5, 5 million people. Many of these systems are made following technologies of 30 – 40 years old and are obsolete and worn out [2]. Although in the last few year it has been tried to modernize and develop the structure, especially in the distribution side, the systems still have low efficiency, great

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losses and also high production and distribution costs. These costs are difficult to pay for the customers and this situation generates important social pressures.

The continuous decrease of the services quality and the rise of the energy costs led to the distrust of the consumers regarding these systems. In 2003, 21% of the initially connected apartments cut the lead with the district heating suppliers [2]. The efficient functioning of the centralized heating sector so it can provide the thermal energy at reasonable prices is the only capable measure to sustain the smooth working of centralized systems.

The theoretical study developed in this paper goes with the actual concerns (nationally and internationally manifested) of improving the thermal energy supplying in district heating systems. The interest is focused on the evaluation of the energy and exergy losses in the pipelines network that highly affect the performance of the heating systems. The total length of the pipe networks in Romania is 11900 km, so that the energy losses are considerable [2].

In the present paper, mathematical models and computational programs are proposed for the determination of the heat losses to the environment, the friction losses and the temperature drop along the pipe segment. Also, an exergy analysis was developed which has proven to be a powerful tool that can be used to detect and to evaluate the causes of the thermodynamic imperfections of the transport process of the hot water.

Phetteplace [3] observed that the dissipated heat in frictional water transportation can be considerable. That is why he considered it into the geometrical optimization algorithm of the hot water distribution systems by economical criteria. Having this observation as starting point, for increasing the accuracy of the numerical results, in this paper we considered the friction influence on the heat transfer between hot water and environment and also on the temperature received by the consumer.

2. Mathematical formulation

The system considered in this study is an insulated buried pipe segment of inner diameter d_i and length *L*. The pipe supplies hot water in a stream of mass flow rate $\dot{m}$ and local water temperature *T*. One-dimensional steady flow is developed and friction and heat losses are taken into consideration.

2.1. Energy losses

The energy analysis is based on the following equations:

- *pumping power* $\dot{W}_p$,

$$\dot{W}_p = \frac{\dot{m} \cdot \Delta p}{\rho} \quad , \tag{1}$$

where the pressure drop Δp is calculated using the *Darcy- Weisbach equation*

$$\Delta p = f \frac{L}{d_i} \rho \frac{v^2}{2} \quad . \tag{2}$$

- *heat losses* $\dot{Q}_{loss}$,

$$\dot{Q}_{loss} = \frac{T_m - T_g}{R_t} \cdot L \quad . \tag{3}$$

where T_m is average water temperature along the pipe segment, $T_m = (T_s + T_e)/2$.

The hot water temperature at the exit of the pipe T_e is determined on the basis of the energy balance equation applied to an elementary segment pipe of length *dx:*

$$-m \cdot c_p \cdot dT = q' \cdot dx - \dot{W}'_p \cdot dx \quad , \tag{4}$$

where heat loss q' and pumping power $\dot{W}'_p$ on unit length are

$$q' = \frac{T(x) - T_g}{R_t} \quad \text{and}$$

$$\dot{W}'_p = \frac{f \cdot 8 \cdot \dot{m}^3}{\pi^2 \cdot \rho^2 \cdot d_i^5} \quad . \tag{5}$$

The overall thermal resistance R_t is found by adding the resistance of the soil to that resulting from the pipe, fluid and insulation. The complete formula is

$$R_t = \frac{1}{\pi h_i d_i} + \frac{1}{2\pi k_p} \ln \frac{d_e}{d_i} + \frac{1}{2\pi k_{ins}} \ln \frac{d_{ins}}{d_e} + \frac{1}{2\pi k_m} \ln \frac{d_m}{d_{ins}} + \frac{1}{\lambda_s} \ln \frac{4H_p}{d_m} \quad . \tag{6}$$

Finally, result

$$T_e = T_g + R_t \cdot B + \left[\left(T_s - T_g \right) - R_t \cdot B \right] \cdot e^{-\frac{L}{\dot{m} \cdot c_p \cdot R_t}} \quad . \tag{7}$$

The convection heat transfer coefficient inside the pipe h_i is calculated with

$$\frac{h_i \cdot d_i}{k_i} = 0{,}023 \cdot \mathrm{Re}^{0{,}8} \cdot \mathrm{Pr}^{0{,}4} \quad , \tag{8}$$

corresponding to a turbulent flow regime.

The programs works with actual values of friction factor f given by Frenkl relation [4].

The temperature of the soil depends on the weather conditions. At the air temperature $T_\infty = -10^\circ C$ and air temperature $\varphi = 60\ \%$ result $T_g = -6{,}8^\circ C$.

2.2. Exergy losses

Frictions inside the pipe and heat transfer to the surroundings during the hot water transportation are identified like main sources of irreversibility. According these, exergy rate losses are quantified with formulas [5, 6]:

- *exergy losses due to the water transportation* (pumping work exergy loss)

$$\dot{E}x_{loss,\dot{W}_p} = \dot{W}_p - \frac{T_m - T_\infty}{T_m} \cdot \dot{W}_p = \frac{T_\infty}{T_m} \dot{W}_p \quad . \tag{9}$$

- *exergy losses during the heat transfer* (heat exergy loss)

$$\dot{E}x_{loss,\dot{Q}_{loss}} = \frac{T_m - T_\infty}{T_m} \dot{Q}_{loss} \quad . \tag{10}$$

Electrical pumping energy $\dot{W}_p$ represents pure exergy that is used to overcome the flow resistance in the pipe. It is transformed by friction into heat and it is « recovered » by fluid. The exergy of the dissipated heat at average temperature T_m is much lower than the exergy $\dot{W}_p$. The difference represents the exergy losses during the hot water transportation.

3. Results

Energy and exergy analysis corresponding to the hot water transportation within the insulated buried pipe is developed for following geometrical and operating data: L = 1000 m; d_i = 0,082 m; d_e = 0,0889 m; d_{ins} = 0,131 m; d_m =

0,140 m; $H_p = 1$ m; $k_e = 0{,}0005$ m; $k_{ins} = 0{,}03$ W/mK; $k_m = 0{,}16$ W/mK; $k_{pipe} = 54$ W/mK; $k_s = 1{,}2$ W/mK; $T_g = -6{,}8$ °C; $T_\infty = -10$ °C .

The computational programs were perform for $\dot{m} = 14$ kg/s and inlet temperature of 40-120°C for study of the influence of the inlet water temperature and $T_s = 40$ °C and mass flow rate of 1-20 kg/s for analysis of the influence of the mass flow rate. The numerical results are presented in figures 1-9. The relative work exergy loss and relative heat exergy loss are defined like

$$\frac{\dot{E}x_{loss,\dot{W}_p}}{\dot{E}x_{loss,\dot{W}_p} + \dot{E}x_{loss,\dot{Q}_{loss}}} \text{, respectively } \frac{\dot{E}x_{loss,\dot{Q}_{loss}}}{\dot{E}x_{loss,\dot{W}_p} + \dot{E}x_{loss,\dot{Q}_{loss}}} . \quad (11)$$

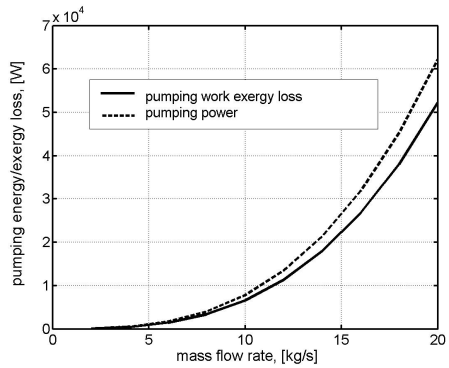

Fig. 1. Pumping energy/exergy loss vs. $\dot{m}$

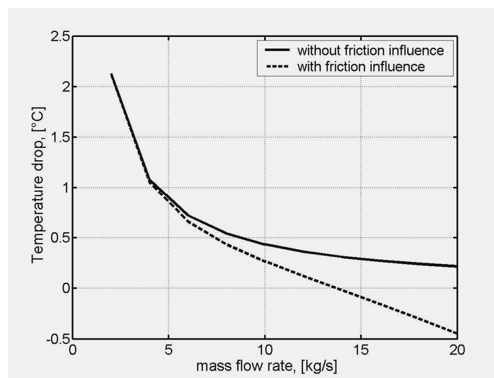

Fig. 2. Temperature drop vs. $\dot{m}$

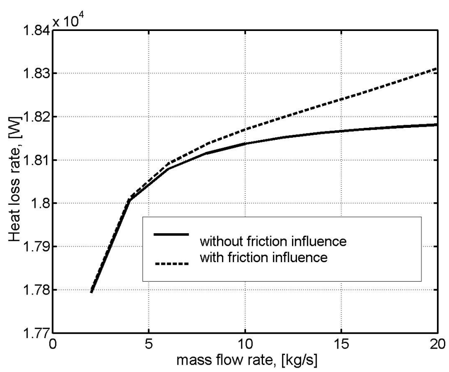

Fig. 3. Heat loss vs. $\dot{m}$

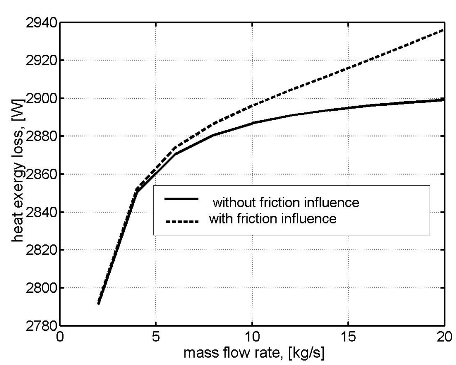

Fig. 4. Heat exergy loss vs. $\dot{m}$

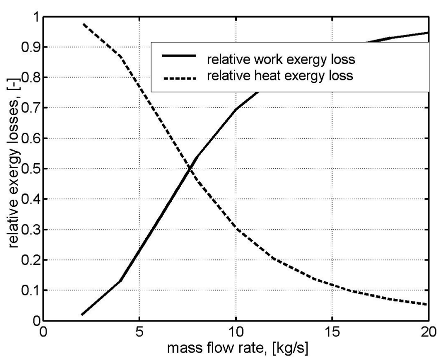

Fig. 5. Relative exergy losses vs. $\dot{m}$

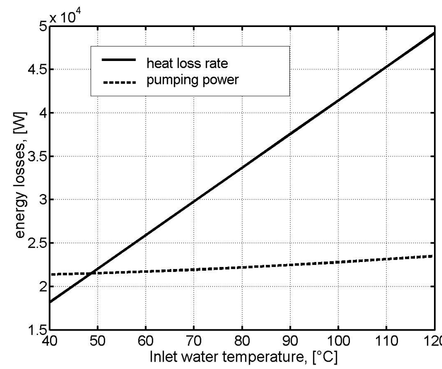

Fig. 6. Energy losses vs. T_S

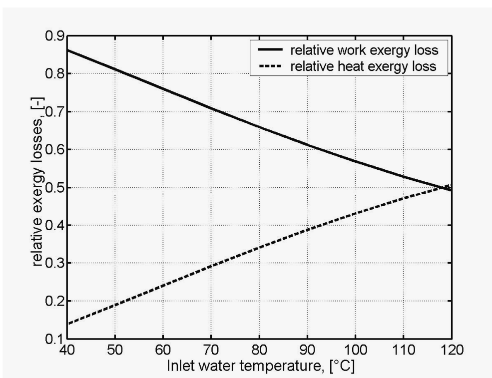

Fig. 7. Relative exergy losses vs. T_S

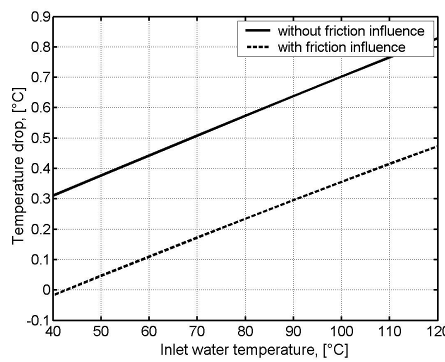

Fig. 8. Temperature drop vs. T_S

4. Conclusions

The quantitative adjustment of the thermal energy supplied by the hot water pipe can be made by varying the mass flow rate in conditions of a constant inlet temperature. Pumping power and corresponding exergy loss are strongly affected by the rise of the mass flow rate (Fig. 1).

The thermal effect of the energy dissipated by friction on the temperature drop along the pipe is noticed at velocity bigger than 1,3 m/s, respectively mass flow rate bigger than 7 kg/s (Fig. 2). The differences between temperature drop with and without considering friction are maximum 0,7 ˚C/km (at $\dot{m}$ =14 kg/s) for a proper insulated pipe.

Both heat loss and exergy loss are affected (Fig. 3, Fig. 4). Also, the rise of $\dot{m}$ in range (1…20) kg/s causes the increase of heat loss and heat exergy loss under 2% /km without friction effect and under 2,8%/km with friction effect.

The contribution of each type of exergy losses on the total value can be followed through relative work / relative heat exergy loss (Fig. 5). At small values of mass flow rate, the heat exergy loss is decisive. At relative great values of $\dot{m}$, the efficiency improvement efforts must be focused on the pumping losses.

As we expected, the increase of the supply temperature affects firstly the heat loss to the environment (Fig. 6). The evolution of the relative exergy losses at the same time with the increase of temperature is illustrated in figure 7. For each interval of temperature it can notice the contribution of each type of irreversibility source on the total exergy loss.

For the considered case, the temperature drop is different if we considered or not the thermal effect of friction. The difference is almost 0,3 ˚C/km and remained constant on the entire temperature range (Fig. 8).

Nomenclature

c_p specific heat, J/kgK
d diameter, m
$\dot{E}x_{loss}$ exergy loss, W
f friction factor
H_p burial depth, m
h_i covection heat transfer coeff., W/m^{2}K
k thermal conductivity, W/mK
k_e rougosity, m
L length pipe, m
$\dot{m}$ mass flow rate, kg/s
Nu Nusselt number
p pressure, Pa
Δp pressure drop, Pa
$\dot{W}_p$ pumping power, W
Pr Prandtl number
$\dot{Q}_{loss}$ heat loss rate, W
q' heat transfer rate per unit lengh,W/m
R_t thermal resistance, mK/W
Re Reynolds number
T temperature, K
v water velocity, m/s
x axial coordinate, m

Greek Letters

ρ water density, kg/m^3
φ relative humidity

Subscript

e exit
i inner
ins insulation
m anvelope
p pipe
s supply
∞ environment
g ground

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