

Investigations of hot water temperature changes at the pipe outflow

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Abstract. In this paper a process of cold water withdrawing from hot water supply pipe systems without recirculation is considered. System of partial differential equations was used to describe the pipe and water temperature changes. An exact solution of a simplified form of the equations was obtained and validated experimentally. The exact solution was applied to calculate the hot water temperature changes at the pipe outflow. Calculations were done for typical pipe materials (PP, PE, Cu), different pipe diameters and lengths as well as for various water flow rates. It was shown that in order to obtain the required hot water temperature in the tap, there is necessary to withdrawn much more (even two times) water from the pipe in comparison to the pipe volume. The reason of such significant water wastes is a heat exchange between hot water flowing inside the pipe and the colder pipe walls. The results can be useful for optimal selection of hot water supply pipes as well as for making decision about applying of hot water recirculating systems.

1 Introduction

Domestic hot water in supply pipes will cool due to heat loss when it will be stagnant for quite some time. In large domestic hot water systems, where the distribution piping is extensive, it will take a relatively long time to remove this cold water from the pipes before the hot water can be available at the tap. This wastes both water and energy are often not acceptable. To overcome this problem, a water recirculation system can be used. Unfortunately some of these systems are very wasteful. According to the regulation [1] the maximum internal volume of the hot water supply pipe for which recirculation system is not required is 3 dm³. The aim of this paper is to investigate the effect of pipe type as well as an influence of flow rate on hot water temperature changes at the pipe outflow. In particular, we are interested in time needed to obtain a required outflow water temperature and mass of water withdrawn from the pipe before the accepted temperature is reached.

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2 Theoretical model

Temperature changes of water (T_c) and pipe (T_r) are described in simplified form as [2]:

$$\tau_c \frac{\partial T_c}{\partial t} + \frac{1}{N_c} \frac{\partial T_c}{\partial z^*} = T_r - T_c \quad (1)$$

$$\tau_r \frac{\partial T_r}{\partial t} = T_c - T_r \quad (2)$$

with boundary conditions:

$$T_c|_{z=0} = T_0 + \Delta T \quad (3)$$

$$T_c|_{t=0} = T_0 \quad (4)$$

$$T_r|_{t=0} = T_0 \quad (5)$$

where:

T_c [°C] – water temperature

T_r [°C] – pipe temperature

t [s] – time

N_c [-] – number of heat transfer units

z [m] – axial coordinate ($z = 0$ at pipe inflow)

$z^* = z/L_r$ [-] – dimensionless axial coordinate

L_r [m] – pipe length

τ_c [s] – time constant of water

τ_r [s] – time constant of pipe

T_0 [°C] – initial water and pipe temperature (cold water temperature)

$\Delta T = (T_1 - T_0)$ [°C] – hot and cold water temperature difference

T_1 [°C] – hot water temperature

In Eqs. (1) and (2), a lumped thermal capacity model [3] for pipe and assumption of uniform radial temperature distribution in water are used. The thermal insulation of the pipe is perfect. Functions N_c , τ_c i τ_r were calculated as follows:

$$N_c = \frac{h_c A_r}{m c_c}, \quad \tau_c = \frac{m_c c_c}{h_c A_r}, \quad \tau_r = \frac{m_r c_r}{h_c A_r}$$

where:

h_c [W/(m²K)] – heat transfer coefficient at the pipe surface

A_r [m²] – pipe internal surface

m [kg/s] – water flow rate

c_c [J/(kg K)] – water specific heat

m_r [kg] – pipe mass

c_r [J/(kg K)] – pipe specific heat

m_c [kg] – water mass in pipe

Heat transfer coefficient h_c was calculated using modified Nusselt equation [4] ($Nu=0.024 Re^{0.786} Pr^{0.45} [1+2.4254/(L_r/d)^{0.676}]$). Transient temperature responses of water at the pipe outflow $T_c = f(t, z = L_r)$ were obtained from exact analytical solution of Eqs. (1)–(5):

$$T_c = T_0 + \Delta T U(N_c, \eta) \exp[-(N_c + \eta)] \tag{6}$$

where:

$$U(N_c, \eta) = \sum_{n=0}^{\infty} \sum_{k=0}^n \frac{\eta^n N_c^k}{n! k!}, \quad \eta = \frac{t - \tau_c / N_c}{\tau_r}$$

3 Model validation

An experimental validation of the theoretical calculation model was accomplished using the experimental set-up shown in Fig. 1. Details of the inlet and outlet of the investigated pipe are shown in Fig. 2. Length of the investigated copper pipe was $L_r = 2.49$ m. Inner and outer diameters of the pipe were $d_1 = 8.183$ mm and $d_2 = 10.0$ mm. The flow rate was measured with the scales and stop watch. The inlet and outlet water temperatures were measured with the transient recorder. Initially in the insulated experimental pipe was cold water, i.e. the water taken from cold water supply pipe. The experimental run was started closing the recirculation hot water loop and opening the supply pipe hot water flow. During the hot water flow the outlet temperature was rising asymptotic until reaching the inlet hot water temperature. The whole temperature history was recorded with the 2 sec step.

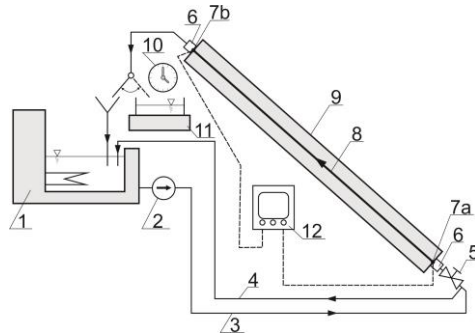


Fig. 1. Experimental set-up, 1 – thermostatic bath, 2 – circulation pump, 3 – supply pipe, 4 – recirculation pipe, 5 – stop and control valve, 6 – connector (thermal insulation), 7a – inflow temperature sensor, 7b – outflow temperature sensor, 8 – investigated pipe, 9 – thermal insulation, 10 – stop watch, 11 – scales, 12 – temperature transient recorder.

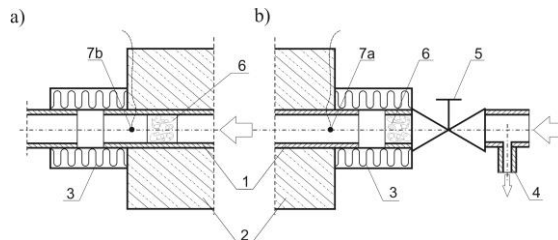


Fig. 2. Details of investigated pipe, 1 – investigated pipe, 2 – thermal insulation, 3 – connector (thermal insulation), 4 – recirculation tap, 5 – stop and control valve, 6 - mixer, 7a – inflow temperature sensor, 7b – outflow temperature sensor.

Comparison between theoretical and experimental results are shown in Figs. 3–5. As is seen, results obtained by means of Eqs. (1)–(5) are about $\Delta t = 10 \pm 2$ s shifted in time (are retarded) in comparison with our experimental data.

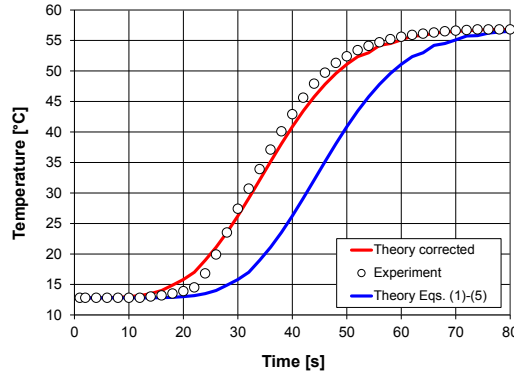


Fig. 3. Comparison of experimental and theoretical results (copper pipe: $d_1 = 8.183$ mm $d_2 = 10$ mm, $L_r = 2.49$ m, $w = 0.166$ m/s, $T_0 = 12.8^\circ\text{C}$, $T_1 = 56.8^\circ\text{C}$, $h_c = 1460$ W/(m²K)).

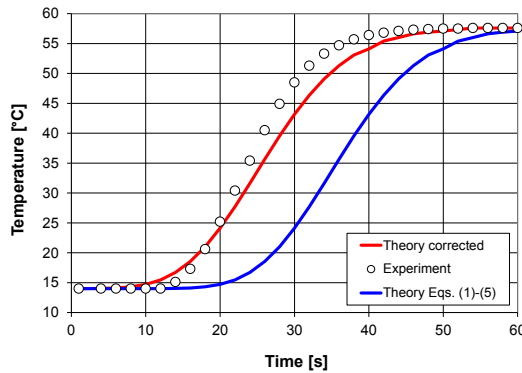


Fig. 4. Comparison of experimental and theoretical results (copper pipe: $d_1 = 8.183$ mm $d_2 = 10$ mm, $L_r = 2.49$ m, $w = 0.242$ m/s, $T_0 = 14^\circ\text{C}$, $T_1 = 57.6^\circ\text{C}$, $h_c = 1960$ W/(m²K)).

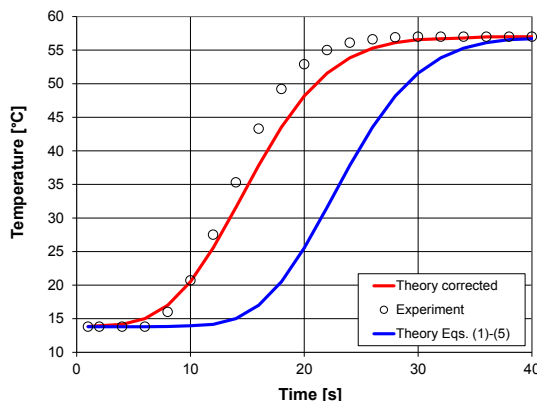


Fig. 5. Comparison of experimental and theoretical results (copper pipe: $d_1 = 8.183$ mm $d_2 = 10$ mm, $L_r = 2.49$ m, $w = 0.435$ m/s, $T_0 = 13.8^\circ\text{C}$, $T_1 = 57.0^\circ\text{C}$, $h_c = 3110$ W/(m²K)).

The differences are slightly higher at larger water velocities and their explanation can be found in simplified form of the theoretical model. Applying simple time correction in form of $(t + \Delta t)$ to the theoretical results it can be obtained a quite good agreement between experimental and corrected theoretical results. Finally, i.e. after “shifting of time axis”, the discrepancies between dots and red lines shown in Figs. 3–5 were found as acceptable.

4 Calculation results

4.1 Effect of pipe type

A corrected theoretical model was applied for calculation of water outflow temperature changes for three standard commercial hot water supply pipes (Table 1).

Table 1. Considered pipes: Cu (copper), PE (polyethylene), PP (polypropylene).

Pipe	d_1 [mm]	d_2 [mm]	L_r [m]	A_r [m ²]	ρ_r [kg/m ³]	m_r [kg]	c_r [J/(kgK)]	Q_r [J]	w [m/s]	h_c [W/(m ² K)]
Cu	13.0	15	22.6	0.9225	8800	8.743	380	132894	1.23	6150
PE	12.0	16	26.5	0.9797	1290	2.949	1620	190665	1.44	7180
PP	14.4	20	18.4	0.8139	905	2.463	2000	197040	1.00	5100

The pipe lengths L_r shown in Table 1 were obtained assuming that each pipe contains 3 dm³ of water. According to the regulation [1], this is the maximum value. Symbols d_1 and d_2 mean inner and outer pipe diameters, respectively. The water velocities w were calculated for the flow rate 163 g/s in each pipe. The temperatures of cold and hot water were $T_0 = 20^\circ\text{C}$ and $T_1 = 60^\circ\text{C}$. Pipe thermal capacity Q_r was calculated as $Q_r = m_r c_r (T_1 - T_0)$. Calculation results in form of outflow water temperature changes are presented in Fig. 6.

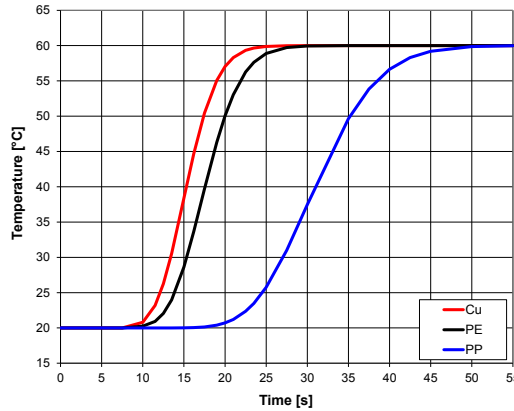


Fig. 6. Water temperature changes at the pipe outflow for 3 different pipes (Table 1) of identical internal volume (3 dm³), the same water flow rate (163 g/s), cold and hot temperatures 20°C and 60°C, respectively.

In Table 2 times t_{55} needed to obtain outflow water temperature of 55°C, and masses m_{55} of water withdrawing from the pipe until the water outflow temperature reaches 55°C are given.

Table 2. Times t_{55} and masses m_{55} for different pipes (pipes data: see Table 1).

Pipe	t_{55} [s]	m_{55} [kg]
Cu	19.0	3.10
PE	22.4	3.64
PP	38.0	6.21

As one can see in Table 1, the PP pipe has the smallest internal surface A_i , the lowest heat transfer coefficient h_c , and the largest heat capacity Q_r . Therefore the intensity of heat exchange between water and PE pipe is smaller in comparison with the Cu and PE pipes. This is the most important cause of the discrepancies in temperature changes shown in Fig. 6. In Table 2 it is seen that for Cu pipe the smallest values of time t_{55} and mass m_{55} were obtained. For this pipe the mass $m_{55} = 3,1$ kg is only a little bit larger than the initial mass of cold water in the pipe. Also for Cu pipe, the time $t_{55} = 19$ s is only 1 s larger in comparison with time necessary to withdrawn the whole cold water from the pipe. For PP pipe, the m_{55} and t_{55} values are two time larger than for Cu pipe. For PE pipe, m_{55} and t_{55} reach intermediate values.

4.2 Effect of water velocity

PE pipe (pipe data: see Table 1) was selected to present the effect of water velocity on outflow water temperature changes. The results are shown in Fig. 7 and Table 3.

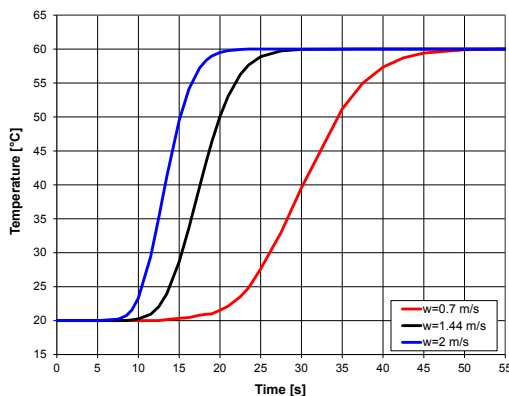


Fig. 7. Water temperature changes at the PE pipe outflow (pipe data: see Table 1) for 3 different velocities: $w = 0.7 \text{ m/s}$ and $h_c = 4160 \text{ W}/(\text{m}^2 \text{ K})$, $w = 1.44 \text{ m/s}$ and $h_c = 7180 \text{ W}/(\text{m}^2 \text{ K})$, $w = 2.0 \text{ m/s}$ and $h_c = 9500 \text{ W}/(\text{m}^2 \text{ K})$.

Table 3. Times t_{55} and masses m_{55} for PE pipe (pipe data: see Table 1) and different water velocities.

w [m/s]	m [g/s]	h_c [W/(m ² K)]	t_{55} [s]	m_{55} [kg]
0.70	79	4160	37.5	2.97
1.44	163	7180	22.4	3.64
2.00	226	9500	17.3	3.85

As is seen, if water velocity increases, time necessary to reach an acceptable outflow temperature decreases and simultaneously mass of waste cold water increases.

5 Conclusions

The simply theoretical model was experimentally verified and introducing a time correction it was found useful for investigations of hot water temperature changes at the pipe outflow. The best hot water supply pipe should have small diameter and low thermal capacity value. Thermal insulation of the pipe ought to be as good as possible. An effect of the hot water flow rate on time needed to obtain a required outflow water temperature and the mass of cold water withdrawn from the pipe were investigated. It was found that with increasing of water velocity a decrease of time necessary to reach an acceptable outflow temperature and simultaneously an increase of losses of cold water are noticeable. The results can be applied for appropriate selection of hot water supply pipes, i.e. length, diameter and material. They can be also useful for making decision about applying of hot water recirculating systems.

References

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