ANALYSIS THE PERFORMANCE OF UNDERGROUND HEAT EXCHANGER

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Abstract

The results of the heat transfer characteristics in underground heat exchanger are presented. The experimental test section is made of 50 m carbon steel pipe of 26.6, 52.5, 77.9 and 102.3 mm inner diameters and 33.5, 60.5, 88.9 and 114.3 mm outer diameters, respectively. The pipe is buried 2 m deep below ground surface. Hot water is used as working fluid in the tube. Experiments are performed under conditions of volumetric flow rates varying from 0.25 to 1 m^3/h and the inlet hot water temperature is between 50 to 80 °C. Water temperature is measured at five points with equal length by thermocouples placed inside the pipe. A mathematical model was developed on this purpose, which allows foreseeing the temperature distribution of the water in the system. Using the model, a parametric analysis was carried out to investigate the effect of water flow rate, pipe material type and pipe length and diameter on the overall performance of the earth tube. Furthermore, a method for estimating soil temperature based on ground investigations is proposed. Moreover, a comparison between experimental results and analytical analysis was conducted under the conditions of experiments. The analytical results agreed well with the experimental results. It is concluded that water flow rate and pipe dimensions are the major variables affect the overall heat transfer process, while pipe material type has a very little effect on the process performance.

Keywords: Heat exchanger, Cooling, Underground, Simulation, Water

تحليل أداء المبادل الحراري المدفون تحت الأرض

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الخلاصة

لقد تم بحث نتائج خواص انتقال الحرارة للمبادل الحراري المدفون تحت الأرض. إن المبادل الحراري ألمختبري قد تم صنعة من أنبوب من الكربون ستيل بطول ٥٠ م و قطر داخلي 26.6 و 52.5 و 77.9 و 102.3ملم و قطر خارجي ٣٣,٥ و ٦٠,٥ و ٨٨,٩ و ١١٤,٣ملم, على التوالي. وتم دفن هذا الأنبوب بعمق ٢ م تحت سطح الأرض. واستخدم الماء الساخن كمائع تشغيل. التجارب أجريت بتغيير معدل التدفق ألحجمي من ٠,٢٥ إلى ١ م٣/سا ودرجة حرارة بين ٥٠ و ٨٠ °م. درجة حرارة الماء تم قياسها في خمسة مواقع متساوية الأبعاد بواسطة مجسات موضوعة داخل الأنبوب. تم حساب نموذج رياضي لهذا الغرض يسمح بتخمين توزيع درجات حرارة الماء في النظام. وباستخدام هذا النموذج الرياضي, تم فحص تأثير معدل تدفق الماء ونوع مادة الأنبوب وطول وقطر الأنبوب على أداء المبادل الحراري المدفون تحت الأرض. كذلك مقارنة بين النتائج المختبرية والنظرية تم إجرائها تحت ظروف التجارب العملية نفسها. النتائج النظرية كانت مقاربة للنتائج العملية. تم استنتاج بان معدل جريان الماء وأبعاد الأنبوب هي المتغيرات الرئيسية المؤثرة على عملية انتقال الحرارة, بينما لوحظ بان هناك تأثير ضئيل لنوع مادة الأنبوب على أداء العملية.

NOMENCLATURE

Notations

Symbol	Mean	Unit
A	Amplitude of soil surface temperature variation	K
C	Degree of cloudiness	-
Cp	Heat capacity	kJ/kgK
d	Diameter of pipe	m
E	Average relative error	-
f	Fraction of evaporation	-
F	Friction factor	-
h	Convective heat transfer coefficient	W/m^2K
J	Solar radiation	W/m^2
k	Thermal conductivity	W/mK
$\dot{m}$	Mass flow rate	kg/s
N	Number of data point	-
Q	Volumetric flow rate	m^3/s
Re	Reynolds number	-
RH	Relative humidity	-
$P*$	Vapor pressure	Pa
Pr	Prandtl number	-
t	Time	s
T	Temperature	K
t_0	Phase constant of soil surface	s
$T*$	Saturated temperature	K
U	Overall heat transfer coefficient	W/m^2K
v	Wind velocity	m/s
w	Annual angular frequency (1.992×10^{-7})	rad/s
x	Coordinate perpendicular to ground surface	m
y	Coordinate parallel to ground surface	m
α	Thermal diffusivity	m^2/s
β	Reflectivity of solar radiation	-
σ	Stephen Boltzmann constant (5.67×10^{-8})	W/m^2K^4

Subscripts

Symbol	Mean
a	Air
d	Direct
exp	Experimental value
in	Inlet conditions
k	Sky
m	Mean value
s	Soil
$theo$	Theoretical value
w	Liquid water
∞	Far field conditions

Introduction

As water for process cooling has become more precious, the re-cooling and re-use of this water have become common. Most often mechanical or natural draft cooling towers are used. In the largest applications, such as re-cooling of the cooling water used in power plants, natural draft cooling towers are often used. Such an installation with the natural draft cooling tower looming over the rest of the plant. Each of these is roughly the size of a football field stood on end, some 90 m tall by 75 m in diameter (Foust et al., 1980).

More performance and \ or reduced the size of heat transfer devices (especially cooling towers) can be achieved by heat transfer enhancement techniques. In general, these techniques can be divided into two groups: active and passive techniques. The use of passive cooling is advisable, with the objective of reducing energy consumption with the acclimatization of spaces. It can thus be an effective tool for attenuating the growth of energy consumption for water cooling. Earth tubes have been used as one of the passive heat transfer enhancement techniques and are the most widely used in heat transfer applications (Silva, 2007).

Since the early exploration of earth tubes use in cooling commercial buildings (Scott et al., 1965), there has been considerable increase in its application. Underground heat exchanger is used to condition the air in livestock buildings (Spengler and Stombaugh, 1983). It is used also in North America and Europe to cool greenhouses (Santamouris et al., 1995). But investigations into the possibility of cooling hot water through a system of earth tubes have never been done before.

Underground heat exchanger is a device that permits transfer of heat from fluid to deeper layers of soil and vice versa. It usually consist of loops of long metallic, plastic or concrete pipe buried in the ground, horizontally or vertically. Vertical loops go deeper. Horizontal loops are usually buried at one to four meters depth. Temperature regime at this depth and beyond is stable, with only a small seasonal (annual) variation and no diurnal fluctuation. This stability due to the fact that temperature waves dampen as they penetrate through layers of soil because ground exhibits high thermal inertia. So large mass of soil at a stable near constant temperature permits it to be used as sink, making the underground heat exchanger capable of cooling (Silva, 2007).

The objective of this paper is to study the heat transfer characteristics of water cooling by underground heat exchanger. To simulate industrial conditions (especially power plants), the temperature ranged from ambient to 80 °C. These data are of value in process and design studies of underground heat exchanger based cooling systems. Based on fundamental equations, a new mathematical model of the underground heat exchanger is developed for practical applications. Moreover, the validity of the model is confirmed by comparing between simulation and experimental results.

Experimental Work

The experiments were conducted in an open garden at the college of Engineering of Alqadissya University in 2009. Soil at the site was examined according to standard tests (ASTM D2216, ASTM D2488 and ASTM D4318) and found to be silt-clay (Sand 9 %, Silt 36 %, Clay 55 %) and has a moisture content of 14 % at the time of excavation.

A schematic diagram and a photographic picture of the experimental apparatus are shown in **Figures 1 and 2**, respectively. The test loop consists of a test section, storage tank, pump, flow meters, and valves. The test section and the connections of the piping system are designed such that parts can be changed and repaired easily. The test section made from carbon steel (1 % C) tubes with a total length of 50 m and constructed by trenching the ground to the 2 m depth. At this depth, earth tubes are mostly immersed in ground water. This improves the heat transfer characteristics of soil (Puri, 1986). The inner diameters of the tubes are 26.6, 52.5, 77.9 and 102.3 mm with thickness of 3.5, 4.0, 5.5 and 6.0 mm, respectively. Five thermocouples (ICM; type: Pt100) are installed to measure the water temperature at five equal positions of the test section. The accuracy of the

thermocouples is 0.1 % and the uncertainty is ± 0.1 of full scale (150 °C). In addition, all thermocouples are pre-calibrated with 0.5 °C precision by using mercury thermometer.

The water temperature in the 1 m^3 storage tank is adjusted to the desired temperature level and controlled by five electric heaters (Reco; type: RT) and a thermostat (Jumo; type: STM2) immersed inside the storage tank. Glass wool was used to reduce the heat lose from the tank. The water is pumped from the storage tank and passed through two flow meters (LZS; type: 2S) and the test section and returned back to the storage tank. The flow rate of the water is controlled and measured by using two valves and flow meters with an accuracy of 0.2 % and uncertainty of ± 0.1 of full scale.

The system operates in the cooling mode between July 15 and August 15, which is the warmer month in the year. Experiments were conducted with various inlet temperature and flow rate of water entering the test section. Before any data were recorded, the system was allowed to approach the steady state. The temperature at each position across the test section were recorded three times and averaged over the time period.

Soil temperature at various depths from ground (0, 1, 2, 3 and 4 m) was measured using a separate vertical probe with five thermocouples. The probe was in place just two meters away from the pipe entrance.

Mathematical Work

A simplified analytical model has been developed. This model assumes that the water in the pipe is in plug flow pattern, such that it can be taken to be at a uniform temperature in the radial coordinate. The flow regime in the pipe is fully developed from the entrance. The pipe is surrounded by a large mass of soil with homogenous thermal and physical properties. So, the amount of heat losses as the water flows through the pipe is equal to the heat transfer between the water inside the pipe and the soil (Mihalakakou et al., 1996):

$$\dot{m}_w Cp_w dT_{w(y)} = \pi dU \left(T_{w(y)} - T_{s(x,t)} \right) dy \tag{1}$$

By integrating equation (1), the following expression can be obtained (where $T_{w(0)} = T_{in}$):

$$T_{w(y)} = T_{s(x,t)} + \left(T_{in} - T_{s(x,t)} \right) exp\left(-\frac{\pi y dU}{\dot{m}_w Cp_w} \right) \tag{2}$$

The overall heat transfer coefficient (U) should be determined using the following equation (Pollet et al., 2000):

$$U = \frac{k_w \left(F/8 \right) \left(Re - 10^3 \right) Pr}{d \left[1 + 12.7 \left(F/8 \right)^{1/2} \left(Pr^{2/3} - 1 \right) \right]} \tag{3}$$

The temperature of the soil ($T_{s(x,t)}$) can be estimated by the following expression with the assumption of homogenous soil of constant thermal diffusivity (Baggs, 1981):

$$T_{s(x,t)} = T_{s,m} - A \, exp\left[-x \left(\frac{\pi}{365\alpha_s} \right)^{1/2} \right] cos\left[\frac{2\pi}{365} \left\{ t - t_0 - \frac{x}{2} \left(\frac{365}{\pi\alpha_s} \right)^{1/2} \right\} \right] \tag{4}$$

Where the average soil temperature ($T_{s,m}$) could be determined by calculating heat transfer rate on the ground surface considering the solar radiation absorbed by the ground, the radiation emitted

from ground surface, convective heat transfer at soil surface and latent heat lossed due to the evaporation of moisture from ground (Krarti et al., 1995):

$$h_s(T_a - T_{s,m}) + [(1 - \beta_s)(J_d\psi + J_k)] = \left| \sigma(273.16T_a)^4 \left(0.474 + 0.076\sqrt{P_w^*}\right)(1 - 0.062C) \right|$$
$$+ \left[0.932\xi h_s(T_w^* - T_a)\right] \qquad (5)$$

Here, the convective heat transfer coefficient on the ground surface (h_s) is given by the empirical correlation of Jürges with respect to wind velocity near ground surface (v).

$$h_s = 5.8 + 3.9v \qquad v \leq 5\,m/s$$
$$h_s = 7.1v^{0.78} \qquad v > 5\,m/s \qquad (6)$$

The appropriate value of the term $\sigma(273.16 + T_a)^4\left(0.474 + 0.076\sqrt{P_w^*}\right)$ $(1 - 0.062C)$ is 58.59~60.48 W/m^2 (Krarti et al., 1995).

The amplitude of the soil surface temperature variation (A) can be determined as follows:

$$A = \left| \frac{h_s(1 + 1.73RH \cdot f)T_a - [(1 - \beta_s)J_d\psi]}{h_s(1 + 1.73f) + (1 + i)\sqrt{\dfrac{w}{2\alpha_s}}k_s} \right| \qquad (7)$$

Results and Discussion

Table 1 shows soil temperature at various radial distances from earth tube. Earth tube heats the surrounding soil. For instance, the table shows that (right at the entrance of the pipe) soil temperature has risen by 39.13 % at the soil pipe interface. As one move farther outward radially, soil temperature returns back to what it was initially. The effected region gets smaller as one move down the pipe due to decrease in fluid temperature. However, at about 70 cm, the effect of the earth tube vanishes. This distance is about 11.67 times pipe diameter. So, this safety distance must be taken into account in designing earth tube systems to avoid adverse effects of soil heating and interaction between earth tubes.

Figure 3 shows soil temperature as a function of depth and time of year. One will notice that soil temperatures are more stable about some averaged value as the depth increases. This will provide useful cooling for hot fluids at a reasonable depth during the year. Although, these data are for Alqadissya, Iraq, they are representative of temperature throughout all of the hot regions of the world. The importance of good ground cover cannot be over emphasized here.

Figures 4 through **6** illustrate the effect of pipe length on the earth-tube temperature distribution. As the pipe length increases, the water temperature decreases, regardless of the other parameters. This is due to the fact that the longer pipe provides a longer path over which heat transfer between the pipe and the surrounding soil can take place. Therefore, a longer pipe should be used if the trenching cost is not prohibitive or the soil thermal properties are bad. However, it can be seen from the figures that at some specific length, the improvements begin to level off. About 70 % of the heat transfer occurs within the first half of the loop (25 m). This result is in agreement with that founded in literature (Deglin et al., 1999).

Figure 4 presents the effect of water flow rate inside the pipe on the water temperature distribution. As the water flow rate increases, the water temperature increases in all positions of the tube, indicating that an earth tube with lower water flow rate will perform better, since the water spends more time in the tube and thus in contact with the lower soil temperature. This can be seen

in the earth tube modeling equations. According to equation (2), a higher water flow rate causes a higher mass flow rate and higher water temperature.

However, when considering the water flow rate during the design process, simply reducing the flow rate does not necessarily improve the earth tube performance since the cooling heat transfer rate due to earth tubes depends on both water flow rate and temperature difference, not on each factor alone. Thus, both water flow rate and temperature decrease should be considered simultaneously. The results of Mihalkakou (Mihalkakou et al., 1996) well agreed with that founded in the present work.

Figure 5 illustrates the effect of pipe diameter on the water temperature distribution. As the pipe diameter increases the water temperature decreases. This is because higher pipe diameter results in a higher heat transfer area on the pipe surfaces. Therefore, a larger pipe diameter should be used for the better performance of the earth tube. It should be noted that the increase in pipe diameter under same water flow rate results in a lower convective heat transfer coefficient on the pipe inner surface and a lower overall heat transfer coefficient on earth tube system due to decrease in water velocity inside the pipe. Thus, pipe diameter and water flow rate should be considered and optimized together.

Figure 6 shows mathematically the type of pipe material effect on the water temperature distribution. It clearly seen that the amount of heat transfer follows the sequence: Carbon steel > Concrete > Fiberglass > PVC. In viewing to the large thermal properties differences between pipe materials, there is only a small variation in heat transfer gain. Therefore, it was concluded that the type of pipe material has very little effect on the earth tube performance and the economic pipe must be used. Also, A number of studies have shown that the pipe material has very little effect on the overall heat transfer in earth tubes (Goswami et al., 1981).

A comparison of the temperature distribution between the analytical analysis and the experimental results are shown in the **Figures 3** to **5**. It is clearly shown that the prediction of the simulation (lines) agreed well with experimental results (points). Furthermore, the prediction accuracy was examined by subjecting to the following formula (average relative error):

$$E = \frac{1}{N} \sqrt{\sum_{i=1}^{N} \left(\frac{T_{i,exp} - T_{i,theo}}{T_{i,exp}} \right)^2} \qquad (8)$$

It was found that the analytical results represent the experimental data with mean average relative error of 2.01 %.

Conclusions

- Pipes of underground heat exchanger must be a part one from other by about 12 times pipe diameter to avoid soil heating and interaction between pipes.
- Dimensions of pipe of underground heat exchanger have large effects on the heat transfer performance.
- Material type of pipe of underground heat exchanger has a little effect on the heat transfer performance.
- Underground heat exchanger is an effective tool for cooling hot fluids in industrial applications.
- Simulation results using the developed prediction model compared with the experimental results and the validity of the model developed herein was confirmed.

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Table 1, Temperature of soil at various radial distances from the earth tube

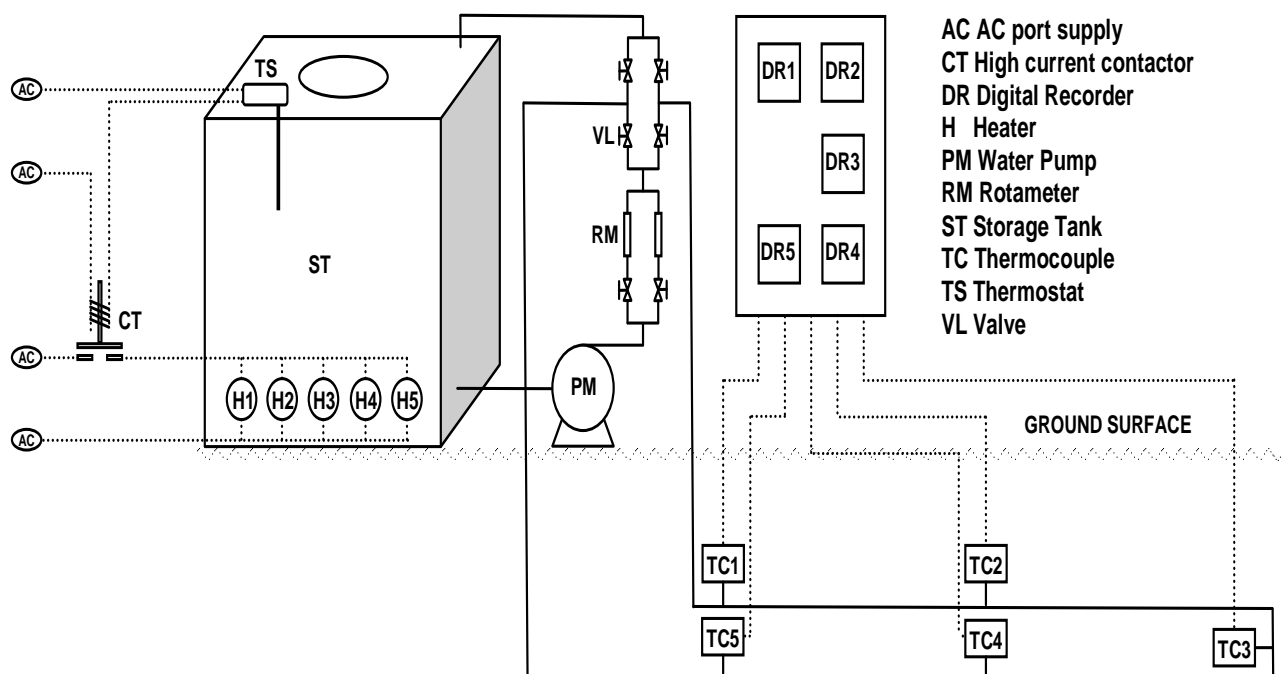| Radial distance, m	$[(T_s-T_{s,\infty})/ T_{s,\infty}]\times100$
0.0	39.13
0.1	21.92
0.2	11.92
0.3	4.23
0.4	1.53
0.5	0.76
0.6	0.38
0.7	0.00
0.8	0.00
0.9	0.00
1.0	0.00

Figure 1, Schematic diagram of experimental apparatus used for underground heat exchanger tests

Figure 2, Photographic picture of experimental apparatus used for underground heat exchanger tests
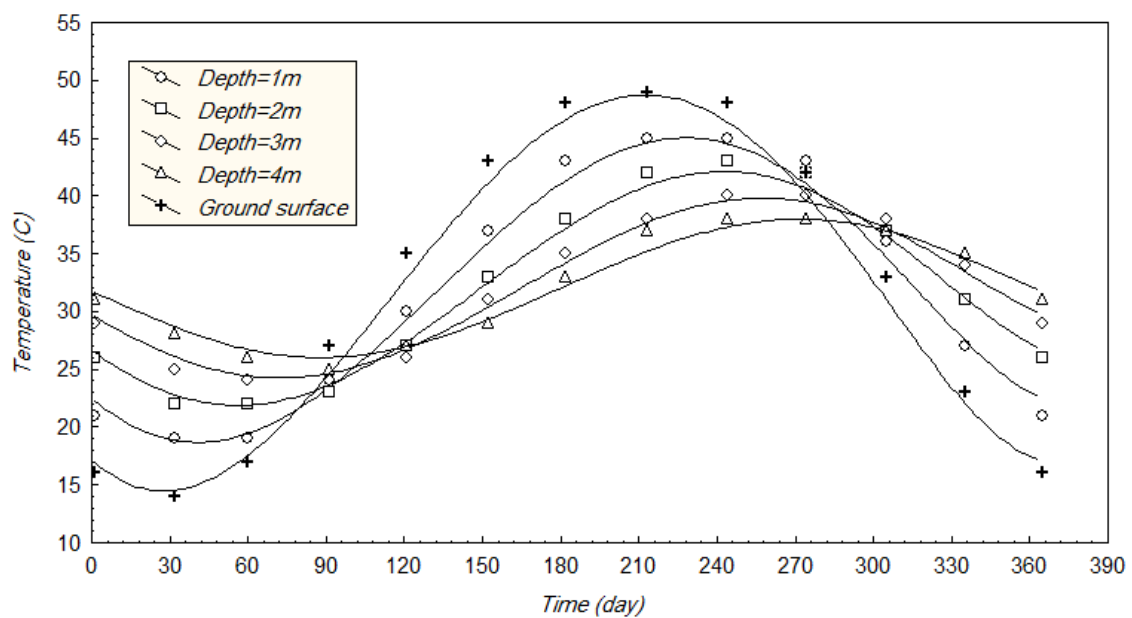
Figure 3, Soil temperature as a function of depth and time of year (Calendar starts at January 1)
(Lines refer to mathematically predicted curves; Points refer to experimentally calculated data)
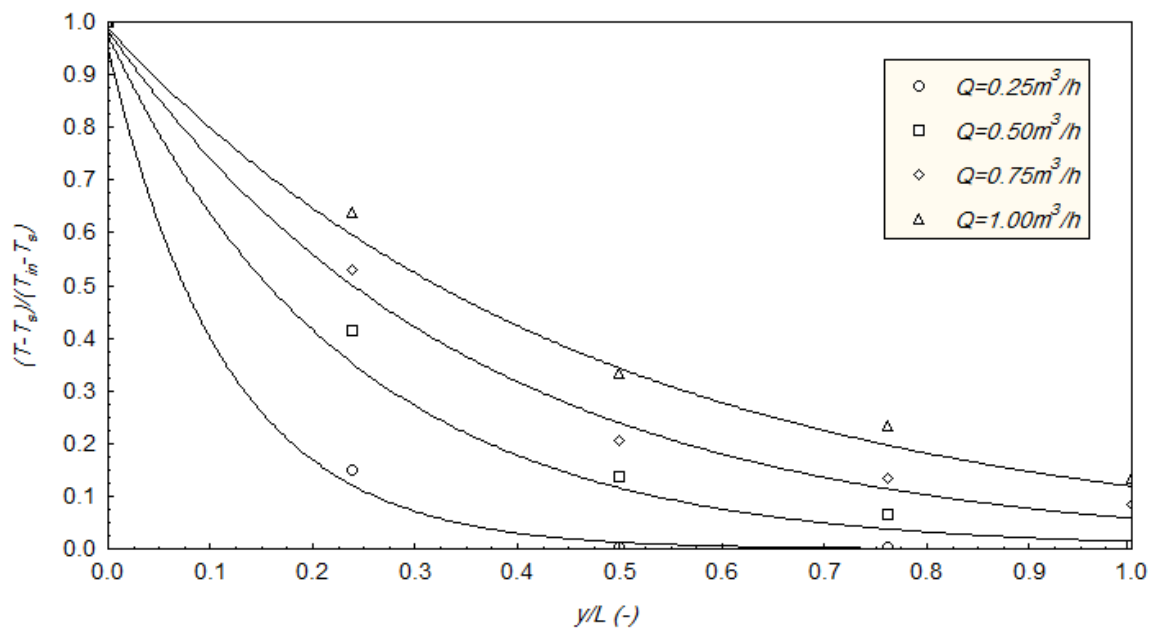
Figure 4, Variation of water temperature with pipe length for different water flow rate
(Lines refer to mathematically predicted curves; Points refer to experimentally calculated data)
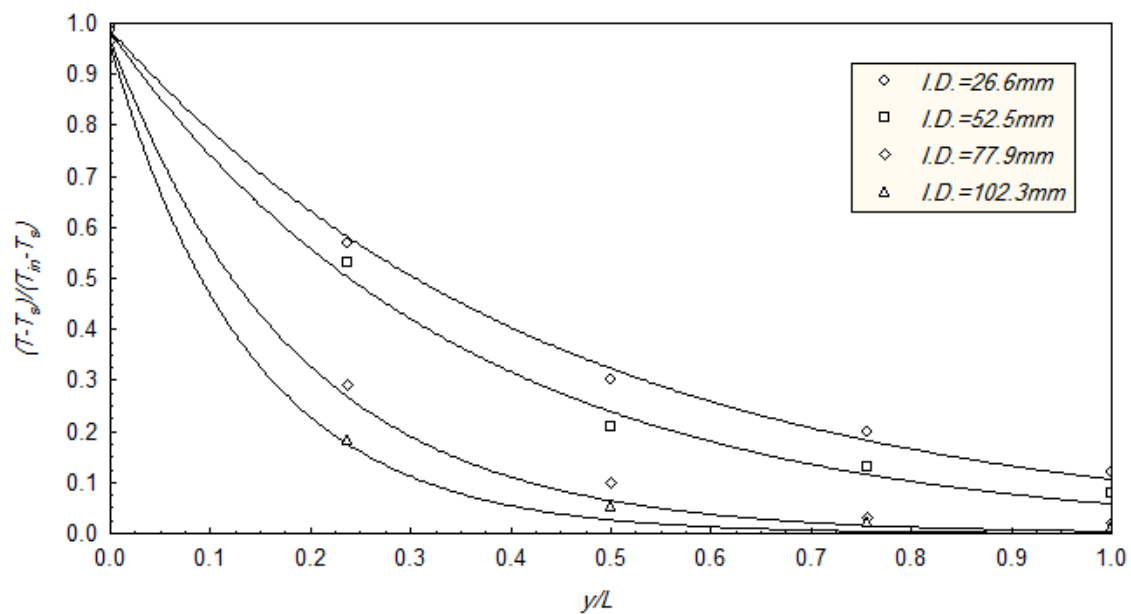

Figure 5, Variation of water temperature with pipe length for different pipe diameters
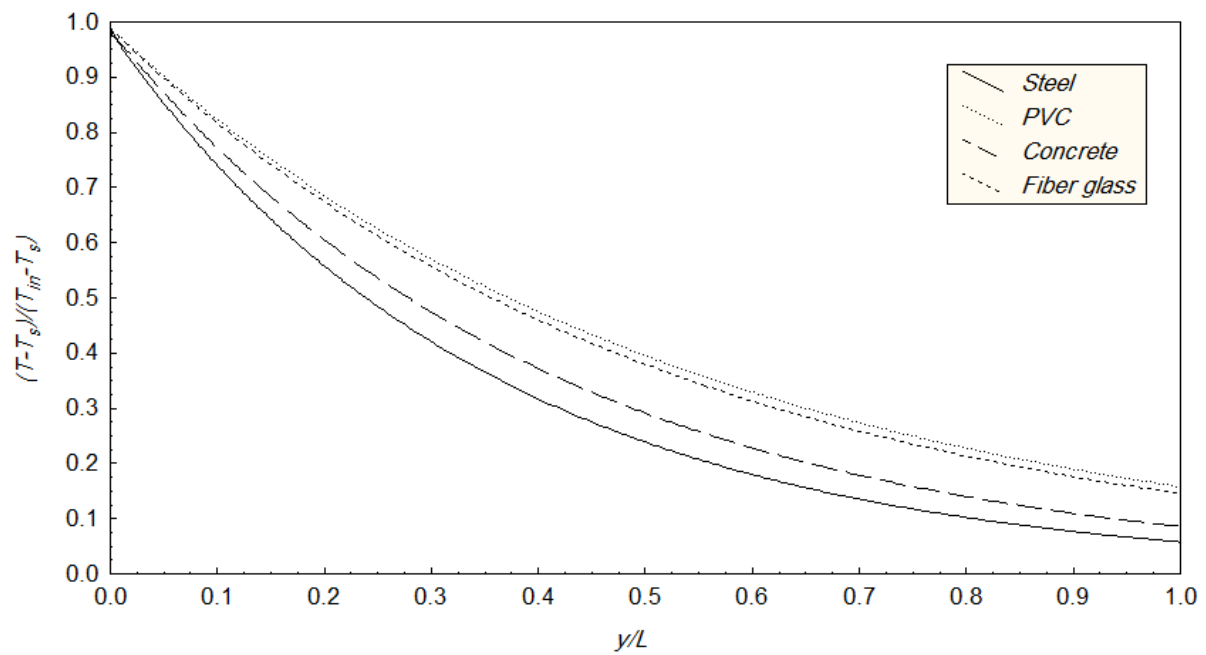(Lines refer to mathematically predicted curves; Points refer to experimentally calculated data)

Figure 6, Variation of water temperature with pipe length for different pipe material types
(Lines refer to mathematically predicted curves)