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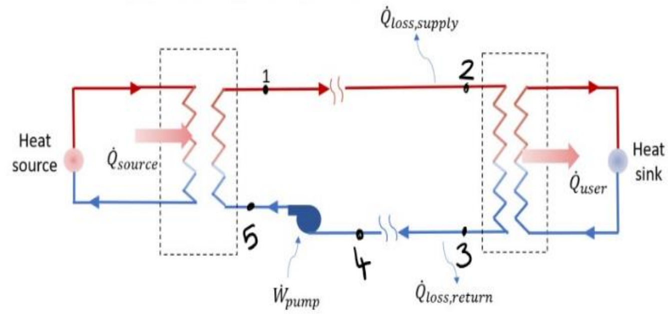
1) Measurements



- To evaluate the energy efficiency, we need the enthalpies at various points, and the total mass flow rate of the system to determine the necessary heat rates. To find the enthalpies, the temperatures and pressures at the appropriate locations must be measured. The total fluid velocity must be found point assuming it is a closed system, and there is no leakage.

- At locations 1, 2, 3,4, and 5, the temperature must be measured (in ℃)
- At locations 1, 2, 3,4, and 5, the pressure must be measured (in kPa)
- At location 4, the water flow velocity must be measured (in m/s). It can be at any location, I chose 4.

2) Equipment and Instrumentation

- A simple positive displacement water flow meter should be employed to measure the volumetric flow rate of water in the overall system. These meters are best suited for this applicated as they do not induce any permanent pressure changes, need to be installed vertically, have any electrical constraints, or lead to any potential gaps on the outside of the tube (like orifice plates). Assuming no leakage, the water will be clean. The heat exchanger system will also not be operating at a low flow rates, so friction will not impact the flow rate measurement. Long range data gathering is possible with this equipment since the data can be converted into electrical signals.

- For all the temperature measurements, a thermocouple or a thermistor would be the easiest to use. But a thermocouple is more accurate, less fragile, and can measure a temperature range below 90℃. A type K thermocouple would suffice for this application since the sensors need not be highly sensitive and the temperature range of $-200 - 1350$℃ is large. Thermocouple are good for long range data collection since the data can be converted into electrical signals.

- For all the pressure measurements, a capacitance elastic diaphragm gauge is a good option as the data can be transmitted to a data acquisition system far away from the pipes. These gauges are also accurate and have a good range of 1000 PA-1400 MPa which is a large enough range for this application.

- Data coming from the flow meters, thermocouples, and elastic diaphragm gauges will travel via underground fiberglass lines and store on a data log server at the district heating system office.

3) Set of Independent Equations and Assumptions

Assume:

- Negligible height changes in the district heating system
- System is a closed system at steady state (no leakages)
- Ignore heat generation from friction due to pressure loss
- Distance between the pump and source is small enough to ignore effects of any pressure losses
- Negligible pressures losses at source and user heat exchangers
- All dimensions and properties of the supply pipe (hot water) are the same as for the return pipe (cold water). This includes inner and outer diameters, material, insulation thickness, and insulation material.
    - Pipe material is Polybutene-1
    - Insulation material is closed cell polyolefin foam
- Incompressible fluid
- Negligible kinetic and potential energies of the fluid
- System is static so no kinetic and potential energies of the system
- Constant soil temperature
- Single pipe, not double insulated pipes

$$\dot{m}_{water} = \rho V_{water}\,(\pi \mathrm{r}_\mathrm{i}^2)\ \ [\mathbf{1}]$$

$$\dot{W}_{pump} = \frac{gH\dot{m}_{water}}{\eta_{pump}}\ \ [\mathbf{2}]$$

Variable	Constant and Specific Levels	Description
$\dot{m}_{water}$	- Kg/s	Mass flow rate of water throughout the system
ρ	997 $\mathrm{kg/m^3}$	Density of water
V_{water}	2, 5 m/s	Speed of the water (flow rate can be measured by the flow meter)
$\mathrm{r_i}$	10.6, 21.3, 38.3 mm	Inner radius of pipe (for both hot and cold pipes)
g	9.81 $\mathrm{m/s^2}$	Gravity constant
H	1, 0.5 m	Pump Head Pressure (Converted to kPa)
η_{pump}	0.90	Efficiency of the pump chosen by experimenter
h	- kJ/kg	Enthalpy determined at different locations based on the pressure and temperature measurements

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_{in}(h_{in} + KE_{in} + PE_{in}) = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out}(h_{out} + KE_{out} + PE_{out})$$

$$\sum \dot{m}_{in}h_{in} = \dot{Q}_{out} + \sum \dot{m}_{out}h_{out}$$

$$\dot{Q}_{source} = \dot{m}_{water}(h_1 - h_5)\ \ [\mathbf{3}]$$

$$\dot{Q}_{user} = \dot{m}_{water}(h_2 - h_3)\ \ [\mathbf{4}]$$

$$\dot{Q}_{loss-supply} = \dot{m}_{water}(h_2 - h_1)\ \ [\mathbf{6}]$$

$$\dot{Q}_{loss-return} = \dot{m}_{water}(h_3 - h_4)\ \ [\mathbf{6}]$$

Looking at the cross section of Locations 2 and 3, the heat losses through the pipes could be derived using the following equations:

$$\dot{Q}_{loss-supply\text{ at 2}} = \frac{2\pi L(T_2 - T_{soil})}{\frac{ln(r_o/r_i)}{k_{pipe}} + \frac{ln(r_s/r_o)}{k_s}}$$

$$\dot{Q}_{loss-supply\text{ at 3}} = \frac{2\pi L(T_3 - T_{soil})}{\frac{ln(r_o/r_i)}{k_{pipe}} + \frac{ln((r_0 + \mathrm{t})/r_o)}{k_s}}$$

This gives an idea of how the variables specified below could potentially affect the system

Variable	Constant and Specific Levels	Description
L	2000 m	Total length of pipe (for both hot and cold pipes)
T_{soil}	15℃	Average temperature of soil
r_o	12.5, 25, 45 mm	Outer radius of pipe (for both hot and cold pipes)
r_i	10.6, 21.3, 38.3 mm	Inner radius of pipe (for both hot and cold pipes)
t	10, 15 mm	thickness of insulation (for both pipes)
k_{pipe}	0.19 Btu/mK	Conduction coefficient of pipe for both
k_s	0.037 W/mK	Conduction coefficient of insultation for both

4) Energy Balance and Updated Efficiency Equation

$$\sum E_{in} - \sum E_{out} = \Delta E_{District\ Heating\ System} = 0$$

$$E_{in} - E_{\mathrm{out}} = 0$$

$$(\dot{Q}_{source} + \dot{W}_{pump}) - (\dot{Q}_{\mathrm{user}} + \dot{Q}_{loss-supply} + \dot{Q}_{loss-return}) = 0$$

$$\dot{Q}_{source} + \dot{W}_{pump} = \dot{Q}_{\mathrm{user}} + \dot{Q}_{loss-supply} + \dot{Q}_{loss-return}$$

$$\dot{Q}_{\mathrm{user}} = \dot{Q}_{source} + \dot{W}_{pump} - \dot{Q}_{loss-supply} - \dot{Q}_{loss-return} \quad [\mathbf{7}]$$

$$\eta = \frac{\dot{Q}_{source} + \dot{W}_{pump} - \dot{Q}_{loss-supply} - \dot{Q}_{loss-return}}{\dot{Q}_{source} + \dot{W}_{pump}} \quad [\mathbf{8}]$$

5) List of Factors

1) Thickness of the cold-water pipe	7) Insulation material of the cold-water pipe
2) Thickness of the hot-water pipe (HI)	8) Insulation material of the hot-water pipe (HI)
3) Outer diameter of the cold-water pipe	9) Insulation thickness of the cold-water pipe
4) Outer diameter of the hot-water pipe (HI)	10) Insulation thickness of the hot-water pipe (HI)
5) Material of the cold-water pipe	11) Pump head pressure
6) Material of the hot-water pipe (HI)	12) Flow rate of the pump (HI)

6) High Impact vs. Low Impact

I choose my high impact factors (HI) to be the thickness, outer diameter, material, insulation thickness, and insulation material of the hot-water pipe, and the flow rate. Either pump head pressure or flow rate would significantly determine the pump power input so I just choose flow rate since it would be easier to vary it, thus the pump head is a low impact factor. The thickness, outer diameter, material, insulation thickness and material of the cold-water pipe will be low impact factors since I assumed all those dimensions are the same as for the hot-water pipe.

7) Factors, Levels, and Experiments

			Level		
			1	2	3
Factor	A	Thickness of the hot-water pipe	2 mm	3 mm	5 mm
	B	Outer diameter of the hot-water pipe	25 mm	75 mm	90 mm
	C	Insulation thickness of the hot-water pipe	10 mm	15 mm	
	D	Fluid velocity delivered by the pump	2 m/s	5 m/s	

My factor considerations came from my high impact factors. One of the high impacts factors was the material of the pipes and insulation. I decided to choose one material for both and choose common materials used in industry. Based on article [1], Polybutene-1 pipes combined with closed cell polyolefin foam insulation was common. I chose to vary the thickness and outer diameter of the pipes. Since I decided to make the diameters the same for both the cold water and hot water pipes, I am not going to worry about the other diameter factors. I chose the outer diameter levels to be 25, 75, and 90 mm to test low, medium, and high values based on diameters used for this application based on Polybutene-1. The corresponding thicknesses align with what is standard as gathered from article [1]. Based on the same article, it is reasonable to use 10-15 mm thick closed cell polyolefin foam insulation Flow rate is a big part of work input. Determining the best velocity which would decrease the heat losses and increase efficiency is important. I chose 2 m/s and 5 m/s as I found those velocities to be common for water pipelines. Plus, I did not want to vary them by too much so that excessive pressure differences would be avoided.

Generally, to increase the efficiency, larger inner diameters, thicker insulation, and thermally non-conductive material is preferable. But to save costs, insulation and pipe sizes must be smaller, and power consumption by the pump should be minimized.

		A1		A2		A3	
		C1	C2	C1	C2	C1	C2
B1	D1						
	D2						
B2	D1						
	D2						
B3	D1						
	D2						

My general approach to the experiments is to make sure each level is tested at least twice. This will help narrow down the best possible combination of parameters, as it would show enough a relationship between each set. For the extra tests, the highlight is darker. I thought testing the 75mm pipe thickness and each velocity would affect the velocity.

References

[1] https://www.pbpsa.com/district-energy