Final Report

EML4512 – Thermal Fluid Design

Group 1

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Abstract

This report outlines Group 1's analysis and comparison of initial and modified piping networks for a newspaper printer facility using solvent based ink. Five printing presses connected to the piping system draw ink as needed at a flow rate of 1L/s each. The intention of the modification to this network was to increase the performance of the network. Throughout the project, Group 1 determined the best type of solvent base ink to use for such an application, as well as the properties of that ink. Group 1's analysis showed that this modification was not cost effective. The group suggested an alternative design, which would significantly decrease the cost of the network by approximately 50% and significantly increase its overall efficiency. A rotary vane pump was also selected as the best pump to use for the network. As dictated by the problem statement, a heat exchanger was also designed in order to compensate for a 10^0C temperature increase in the ink as it flowed through the network. The required length for the double pipe heat exchanger designed by Group 1 was found to be approximately 29m. The group determined a method of arranging this heat exchanger in a space-efficient manner.

Project Background

The purpose of this project is to analyze and compare two different piping networks for a newspaper company. Before the ink is pushed through the network, it is stored in a tank where the ink is constantly being mixed to maintain a uniform mixture. The ink is then transported upward into the celling suspended network to travel throughout the facility into each of the five printing presses.[1]

The ink is pumping through the network constantly, allowing the printers to use the ink as needed. Excess ink bypasses the printers going to a return line and back into the tank. As the ink travels in the network, a temperature rise of 10°C occurs. Due to this temperature rise, environmental impact needs to be taken into consideration. For this purpose, it is suggested to use a solvent based ink.[1] The ink chosen is determined by the group. The ink will be soybean oil based, since it is relatively environmentally friendly.[2]

Figure 1 shows the first of the network designs to be analyzed by Group 1.

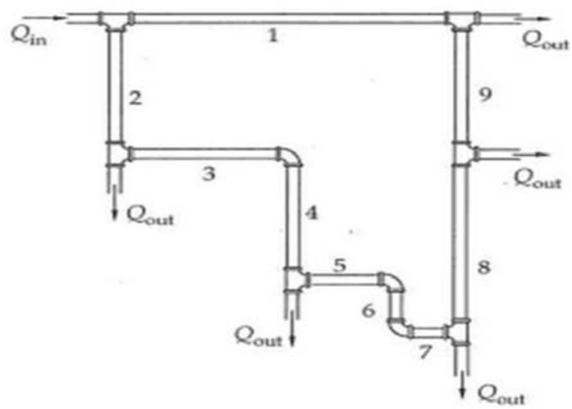

Figure 1. Original ink distribution network.[1]

This network is suspended in the celling of the newspaper company. It shows the locations of the five printer outlets and where the inlet of the network is located. Figure 2 below shows the second, modified network to be analyzed.

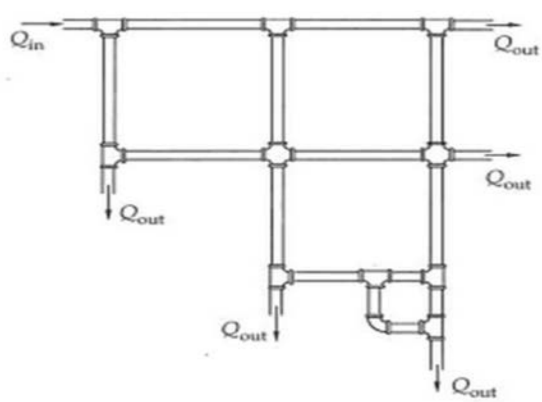

Figure 2. Modified ink distribution network.[1]

By adding the interior lines, it will theoretically lower the overall pressure drop in the system and, therefore, the power requirement of the pump. If true, this would make the system more efficient.

Project Requirements and Specifications

Each printer needs at least 1 L/s of ink in order to operate. The tank needs to provide a minimum of 5 L/s of ink to supply all five printers. Continuous circulation is required to maintain proper ink temperature and mixture. The ink must be a solvent based ink that is environmentally friendly.

For this design project, the group has to determine the necessary colors of ink needed to produce a typical paper. The properties of the ink, its environmental impact, are all inks solvent base or water base, and how the ink is used in the printing process.

For analyzing the piping networks shown in Figures 1 and 2 respectively, it is assumed to use only black ink. Once the ink is chosen, the group will then have to determine the optimum diameter of the pipe and material to minimize cost. Also to determine what other modifications should be considered when analyzing the networks. Once the piping is known, the pump must then be found to meet the minimum 5 L/s requirement.

Lastly a heat exchanger has to be designed to help keep the ink cool from a temperature rise of 10°C. The fluid for the heat exchanger needs to be water with an inlet temperature of 25°C.

Printer Ink Properties

In order to truly understanding the flow properties, the properties of the ink, the working fluid, must be chosen and then evaluated. Printers use a total of four colors: black, yellow, magenta and cyan. Since a newspaper is expendable, and is easily recyclable, the best choice is to use Soybean oil. Soybean oil has a low odor, is easy to recycle, cost effective, and is easy to clean should there be a spill.[2] However, the thermal properties of Soy Bean oil are difficult to come by, and thus calculations cannot be performed. However, Engine oil has very similar fluid properties to Soybean oil and the thermal properties for engine oil are readily available as can be seen in Table 1. Therefore, for heat transfer calculations, properties such as the thermal conductivity and Prandtl number were that of Engine oil.

Another factor that would optimize the piping network is a range of economic velocity. This is a velocity in which the piping network efficiency would be at near max. Too low or too high, then it becomes inefficient to pump the working fluid. Again, for soy bean oil these ranges are hard to find, however Linseed oil is sometimes used to replace Soybean in paints and varnishes, and also shares similar fluid properties. Therefore, as can be seen in Table 1, the economic velocity values for Linseed oil has been used synonymously with that of Soy Bean oil in order to maximize the efficiency of the network.

Table 1. Properties of Soy Bean Oil and other oils used to substitute the properties of Soy Bean Oil which could not be found. The properties used are in bold.

Soy Bean Oil Properties (20°C)[3]	***Engine Oil Properties (20°)***[1]	***Linseed oil Properties (20°C)***[1]
		Economic Velocity Range: 1.5 – 3.0
	k = 0.145	

	Pr = 10,400	

Initial Network Analysis

One of the tasks Group 1 had was to compare two piping networks. The requirement was set for five outlet nozzles to have a flow rate of 1 L/s. The initial piping network needed a recirculation line that would redirect any unused ink back to the initial tank. Group 1 utilized Fathom from Applied Flow Technologies (AFT), which permitted Group 1 a 14-day license for the software. The initial piping network configuration is represented in Figure 3. The tank, J1, and pump, J2, are at an elevation of 0 meters. The outlet pressure of the pump was 175 kPa. The tank and pump flow data can be found in Figure 4. The piping configuration needed to be at the ceiling height of a manufacturing facility. Group 1 selected a ceiling elevation of 3 meters; therefore, Junction 3 has a height of 3 meters. P2 has two 90^0 bends and a length of 6 meters. The velocities for each section of pipe are illustrated on Figure 3. Each nozzle enters a piece of printing equipment at a height of 2 meters; therefore, each set of pipe connecting the nozzle to the piping network has a vertical length of 1 meter. The total length of pipe in the initial piping network was 52.5 meters. The total frictional pressure drop in the initial piping network was 35.4 kPa, and the total stagnation pressure drop was 17.4 kPa. The initial piping network configuration had a total pressure head of 18 meters, eight 90^0 bends, five 3-way tees, and one 4-way tee. Figure 12 in the appendix, illustrates the calculated data for each section of pipe in the initial piping network configuration. The recirculation line, P14, was closed in order to attain the correct flow values through the piping network when all five nozzles were open.

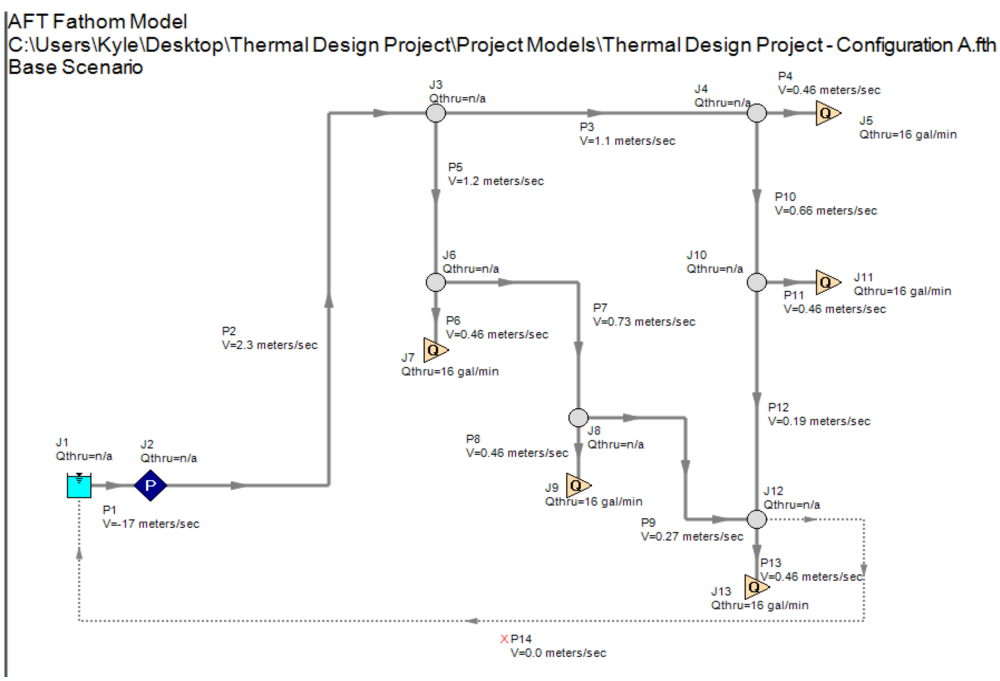

Figure 3. Initial Piping Network

Jct	Name	P Static In (psia)	P Static Out (psia)	P Stag. In (psia)	P Stag. Out (psia)	Vol. Flow Rate Thru Jct (gal/min)	Mass Flow Rate Thru Jct (lbm/sec)	Loss Factor (K)
1	Tank	0.00	1.955	0.00	1.955	N/A	N/A	1.000
2	Pump	N/A	N/A	25.38	25.382	N/A	N/A	0.000

Figure 4. Tank and pump flow data.

Interior Lines Network Analysis

A second piping network configuration was provided to Group 1 in order to compare the findings to the initial piping network configuration. The nozzle outlet locations and required flows remained the same, as well as the tank, pumps, and entrance lines. Several interior lines were added, along with different junctions. Figure 5 illustrates the second piping network configuration with relevant flow properties. The tank and pump flow data remained the same, as well as the piping and nozzle elevations. The velocities for each section of pipe for the second piping network are illustrated on Figure 5. The total length of pipe in the second piping network was 64.5 meters. The total frictional pressure drop in the second piping network was 35.0 kPa, and the total stagnation pressure drop was 17.0 kPa. The second piping network configuration had a total pressure head of 20 meters, six 90^0 bends, seven 3-way tees, and three 4-way tee. Figure 13, in the appendix, illustrates the calculated data for each section of pipe in the initial piping network configuration.

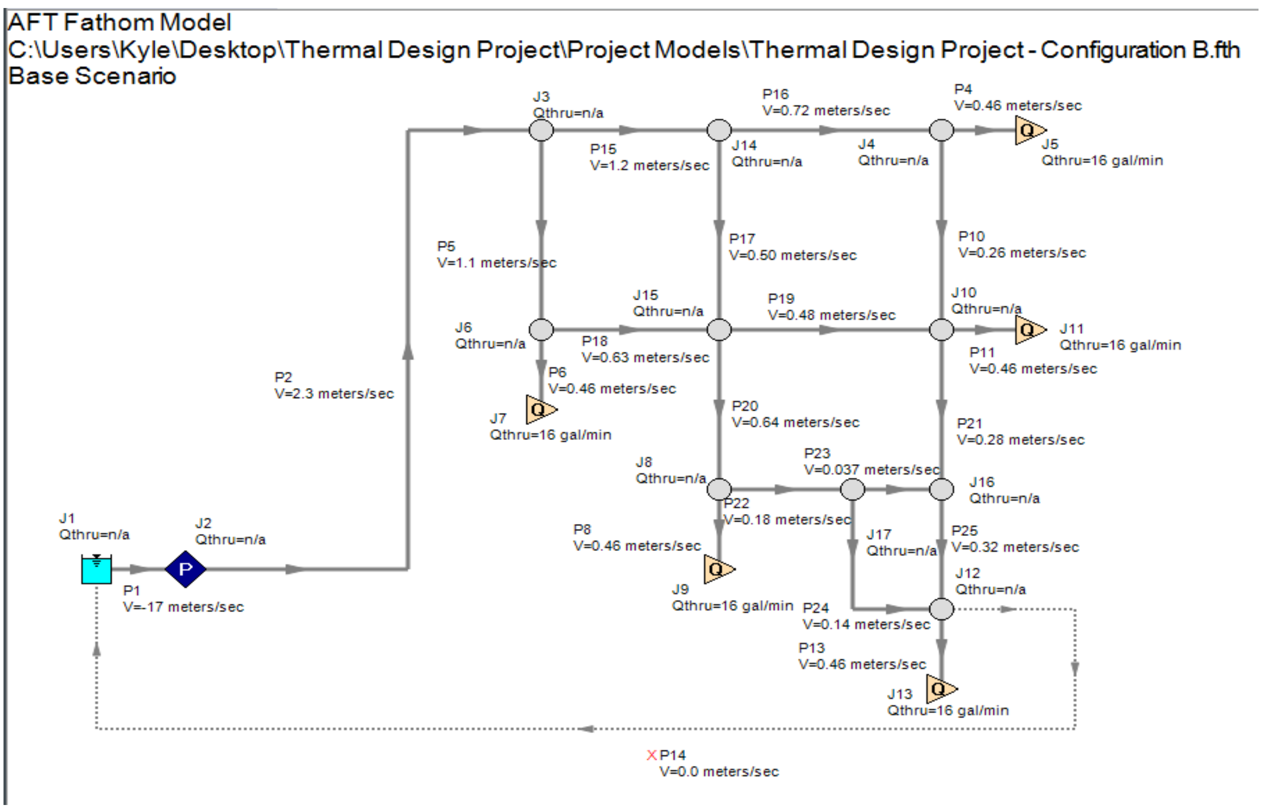

Figure 5. Modified piping network.

Suggested Improvements

Group 1 was asked to suggest improvements to optimize the piping networks provided. Group 1 maintained the pump pressure and all relevant elevations, and recommended that the facility be reorganized. If the printing presses were oriented adjacent to each other, then a singular header may be placed above row of the printing presses. Figure 6 illustrates the recommended piping network configuration. From the header, branches will send the ink directly to the nozzles of the printers. The theory behind this was that it would dramatically reduce the pressure drop, amount of pipe and fittings used, and be easier for maintenance purposes. Because the design of this network also uses a significantly shorter length of total piping, it would also dramatically decrease the cost of the piping network. The recommended piping network had a total frictional pressure drop of 26.5 kPa, total stagnation pressure drop of 8.5 kPa, a total length of pipe of 29.0 meters, and 10 total fittings. Figure 14, in the appendix, illustrates the flow data from the recommended piping network.

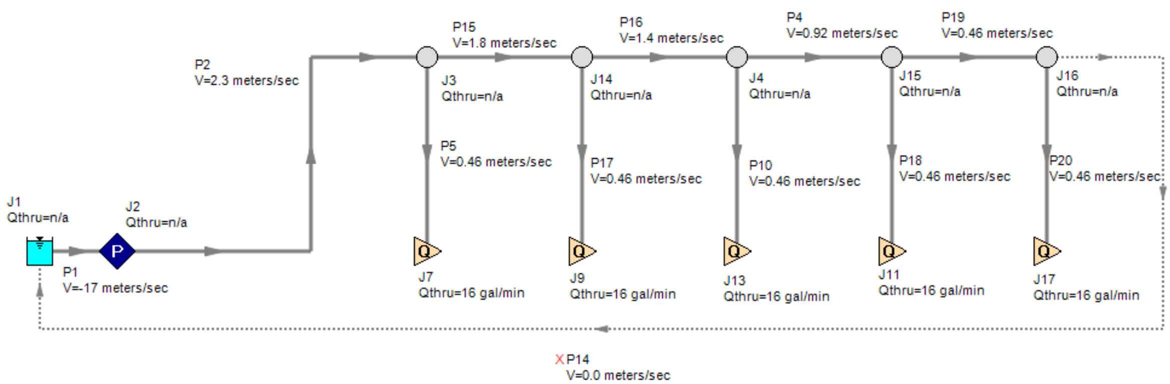

Figure 6. Suggested improvements piping network.

Network Comparison

As can be seen in the Table 2 below, adding interior lines to the network does not improve upon the performance of the piping network much, but rather increases the cost of the materials needed to construct. The frictional losses and stagnation pressure drop are virtually the same but the length of the pipe and fittings increase, thus making the suggested updated network inefficient and not practical. Rather the network created by Group 1 seems to be the best in terms of performance and in cost. As can be seen in Table 2, the frictional losses and number of fittings have decreased, and the stagnation pressure drop, length of the piping needed and cost decrease by almost half.

Table 2. Comparison of the analysis results for each of the three networks.

Network	***Frictional Losses (kPa)***	***Stagnation Pressure Drop (kPa)***	***Length of Pipe (m)***	***Number of Fittings***
Original Network	35.4	17.4	52.5	14
Network w/ Interior Lines	35.0	17.0	64.5	16
Recommended Network	26.5	8.5	29.0	10

Cost Analysis

Group 1 analyzed the cost of each of the piping networks using www.onlinemetals.com to price the piping that would be required.

Table 3. Cost analysis of the original piping network.

Original Network	***Price***
SS 2-Sch. 40 (no fittings)	$2,578.32
"Buy now" Coupons	-$386.75
Total Cost	**$2,191.57**

Table 4. Cost analysis of the modified piping network.

Updated Network	***Price***
SS 2-Sch. 40 (no fittings)	$3,294.52
"Buy now" Coupons	-$494.18
Total Cost	**$2,800.34**

One of the factors in determining whether or not the new piping network is more efficient is to look at the cost. Both of the networks are built from stainless steel, 2 schedule 40 pipes, and the prices for the piping needed for each network are shown in the tables above, note that these prices do not include the fittings that each network would need. The retailer selling the pipes also offers a 15% off coupon in order to make the piping more affordable.

From what could be previously seen in the Network Comparison, the new network with interior lines does not offer very much improvement in terms of pipe flow performance. The increase in performance is nearly negligible, however the increase in cost is not. As can be seen in the Tables above, the total difference in price from the Updated network to the original network is $608.77, which is approximately a 28% increase in price for not much of an improvement.

The group also analyzed the cost of their recommended system. Because the length of piping required was so much shorter than either of the networks proposed in the project, this recommended network resulted in a cost of $1,461.05 for the piping, after applying the suppliers 15% coupon code. This is a reduction of nearly 50% in the cost of the network, and is accompanied by significant increases in flow efficiency. These facts reinforce the strength of Group 1's argument for their recommended network over either of the initially proposed systems.

Pump Selection

The printing system for which Group 1 was designing required that the ink that was supplied from a holding tank be pumped upward to the piping network suspended from the ceiling and out to each of the five presses in the facility. In order for the selected pump to transport soybean oil based ink, it needed to be able to pump high viscosity fluids of at least $6.1\text{x}10^{-5}$ m^2/s or 61 centistokes. The pump needed to be able to provide a minimum ink flow rate of 5L/s or 80gpm. This flow rate accounted for the required 5L/s at the inlet of the piping network with all presses operating, and the flow rate of excess ink, calculated with AFT Fathom, coming from the return line if presses were shut down. The eligible pumps were narrowed down to a screw pump and a vane pump. The screw pump, shown below in Figure 7 was a Bornemann Type Series W/V Twin Screw pump, and it was a potential option due to its flow rate range of 50-12,300gpm, and its ability to handle high viscosity fluids, with a viscosity range of 0.5-200,000 centistokes.

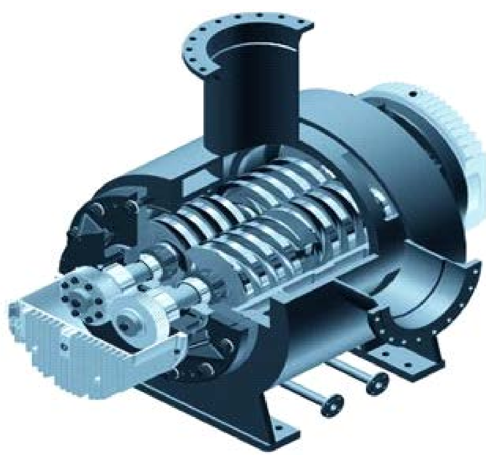

Figure 7. Bornemann Type Series W/V Twin Screw Pump.[5]

The other pump option was a Viking Rotary Vane pump shown in Figure 8. This pump was a more versatile pump in that it could be used with both high and low viscosity fluids. For the purposes of Group 1's design, this pump would be able to handle the ink, having a viscosity range of 0.1-500 centistokes. This particular vane pump was a viable option because it met the requirements for pressure drop, having a range of 0-200psi and a max flow rate of 125gpm.

Figure 8. Viking Rotary Vane Pump LPV41197.[6]

After analysis of the performance curves, shown in Figures 9 and 10 and approximate pricing of both pumps, the Viking Rotary Vane Pump LPV41197 19 series was selected over the Bornemann Twin Screw pump for the printing system. Looking at the performance curve for the Bornemann Twin Screw pump, it is seen that even when using the lowest grade pump, the printing system would require the pump to barely operate at a capacity that would make the purchase of the pump advantageous. The researched price for this pump falls between $25,000 and $70,000, which is far beyond the intended budgetary range for such a project. Upon further research into the application of twin screw pumps, Team 1 realized that such pumps were used for large scale applications, such as oil refineries. The Viking Rotary Vane Pump provided a much more reasonable option. The vane pump met all the aforementioned performance requirements, and from the performance curve in Figure 10, it is shown that the LPV41197 model 08 series, will be used at a more profitable capacity. The 08 series would be able to operate effectively with the needed flow rate of 80gpm and a max total pressure difference of 60 kPa or 8.7 psi. Another benefit to selecting the Viking Rotary Vane pump was that its projected cost would be around $2,500, which is much more reasonable and affordable compared to the twin screw pump price. Overall the Viking Vane Pump LPV41197 08 series was selected because it met the performance constraints, and because it was more cost effective making it a good fit for the printing system piping network being designed.

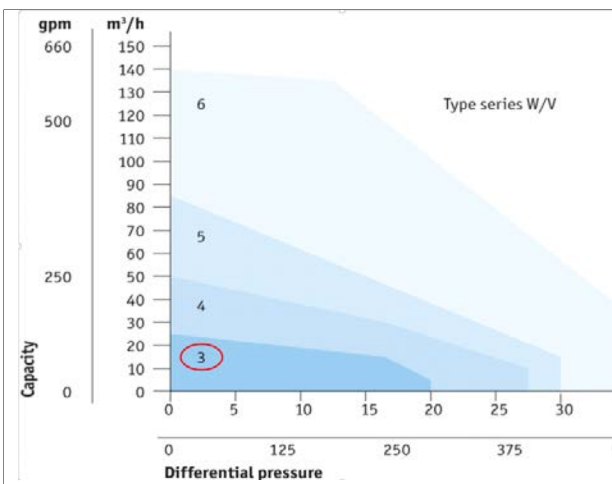

Figure . Bornemann Type Series W/V Twin Screw Pump

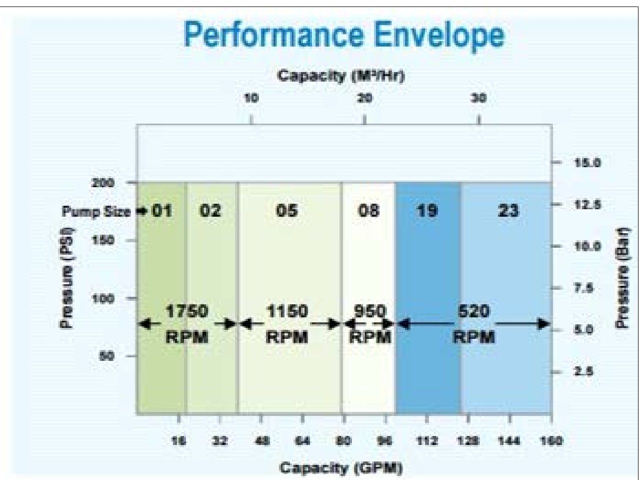

Figure . Viking Rotary Vane Pump LPV41197 Performance

Performance Curve.[3]	*Curve.*[6]

Heat Exchanger Design

The project description asked Group 1 to develop a heat exchanger to compensate for a 10^{0}C increase in the ink temperature. Water was to be used as the cooling fluid, with an inlet temperature of 25^{0}C. No other requirements or constraints were given for the design of the heat exchanger. The final version of the MathCAD code used by Group 1 in the development of the heat exchanger can be seen in the appendix. This code was created after approximately 15 iterations of the design, varying parameters such as piping sizes and flow rates. The piping would be made of the same stainless steel material used throughout the network in order to avoid corrosion from the ink, but it was assumed that the thermal resistance of the pipes would be negligible.

The first step taken by Group 1 was to determine a reasonable temperature range for the ink. Research showed that household, water based inks begin to lose stability above 35^{0}C, but that solvent based inks can withstand higher temperatures.[4] Because the project involved solvent based ink, Group 1 decided to set 35^{0}C as the lower, desired temperature for the ink and 45^{0}C as the upper temperature. The mass flow rate of the cooling water was also defined. This value was iterated several times by the value used in the final design was 16 kg/s.

With the temperatures of the ink and the mass flow rate of the water defined, Group 1 was able to solve for the outlet temperature of the water as well as the total energy transfer from the ink to the water, 86.3kW. The fact that the energy transfer was on the order of kilowatts and not megawatts told Group 1 that a double pipe heat exchanger would be sufficient for this application, rather than using a shell and tube or plate frame heat exchanger. Group 1 decided to use a counter flow double pipe heat exchanger because of the efficiency benefits over a parallel flow design. It was determined that the hot ink would flow in the inner pipe in order to help insulate the heat from the environment of the print shop. After determining the style of heat exchanger, the group was able to find the log mean temperature difference and solve for the overall heat transfer, UA, required by the heat exchanger. This value was found to be 6,207 W/K.

Group 1 then began the determination of the piping sizes to use for the double pipe heat exchanger. Knowing the economic velocity ranges for both the ink and cooling water were 1.5-3.0m/s aided the group in this task, limiting the options that could be chosen from standard piping sizes while still maintaining an economic fluid velocity. Initial choices of piping sizes, combined with the initially defined mass flow rate of cooling water, yielded incredibly long required lengths for the heat exchanger (the solution for the length will be discussed shortly). After iteration, however, the group determined that a 5-2 schedule 40 double pipe heat exchanger was the best choice for the application.

Setting the piping dimensions allowed Group 1 to calculate the annular flow area for the cooling water as well as the hydraulic and effective diameters. These values were then used to find the Reynold's numbers for both fluids and it was determined that the cooling water was flowing turbulently while the ink was experiencing laminar flow. This led to the calculation of the friction factors as well as the Nusselt numbers for both the ink and the water. The Nusselt numbers were then used to solve for the individual heat transfer coefficients of the ink and the water, approximately 443 and 4007, respectively. It is important to note that the heat transfer from the ink is the limiting factor of the design. This can easily be determined from the fact that its heat transfer coefficient is almost 10 times lower than that of the water.

Combining these heat transfer coefficients, along with the fouling factors of the ink and the cooling water, Group 1 was able to solve for the total heat transfer coefficient of the design system. Dividing the originally determined, required overall heat transfer (UA) by this newly found total heat transfer coefficient, it was possible to solve for the required surface area of the heat exchanger. Using the selected piping sizes, it was then calculated that the required length of the double pipe heat exchanger was just under 29m. Again, this final value was determined after many iterations of the design. It was calculated that the associated frictional pressure drop would not be greater than 44kPa for either fluid, which is acceptable.

Although a 29m long heat exchanger seems like a very long design, Group 1 determined that if the design were coiled back and forth on a rack it could be arranged in 10 sections of approximately 1.5m each. An example of a similar design can be seen in Figure 7.

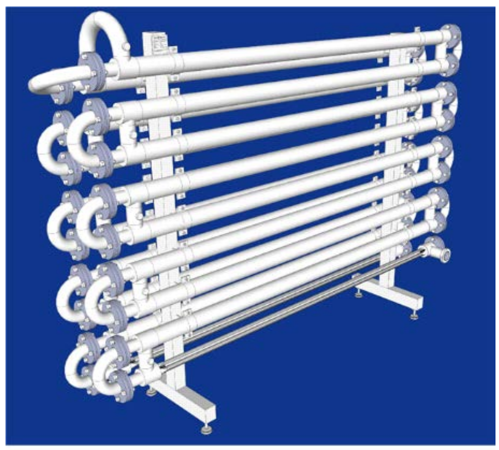

Figure 11. A double pipe heat exchanger wrapped back and forth on a rack.

Setting up the heat exchanger in this manner would make the design much more compact than simply having a 29m long pipe.

Conclusion

Group 1 determined that the addition of interior lines to the existing network would not be cost effective in regards to reducing the pressure drop of the system. The group's recommendation is a reorganization of the facility in order to allow for a single header to supply the required ink to the five printers. Not only would this single header design reduce the losses in the system, but it would eliminate approximately 50% of the piping costs.

A pump was also selected for the ink supply network and a double pipe heat exchanger developed in order to cool the ink from a 10^0C temperature increase caused by energy input of the pump as well as friction in the piping network. It was determined that a vane pump would be the best choice for the network and that approximately 29m of the double pipe heat exchanger design would be required to compensate for the temperature rise of the ink.

Appendix

Initial Piping Network AFT Fathom Data

Pipe	Name	Vol. Flow Rate (liter/sec)	Velocity (meters/sec)	P Static Max (Pascals)	P Static Min (Pascals)	Elevation Inlet (meters)	Elevation Outlet (meters)	dP Stag. Total (Pascals)	dP Static Total (Pascals)	dP Gravity (Pascals)	dH (meters)
1	Pipe	-35.9777	-16.6187	48,441	13,482	0.000	0.000	-34,959.0	-34,959.0	0	-3.88960
2	Pipe	5.0000	2.3096	172,556	133,247	0.000	3.000	39,308.2	39,308.2	26,963	1.37350
3	Pipe	2.4199	1.1178	135,119	127,528	3.000	3.000	7,591.5	7,591.5	0	0.84464
4	Pipe	1.0000	0.4619	136,677	128,003	3.000	2.000	-8,674.1	-8,674.1	-8,988	0.03490
5	Pipe	2.5801	1.1918	135,041	130,994	3.000	3.000	4,046.9	4,046.9	0	0.45026
6	Pipe	1.0000	0.4619	140,221	131,547	3.000	2.000	-8,674.1	-8,674.1	-8,988	0.03490
7	Pipe	1.5801	0.7299	131,401	125,981	3.000	3.000	5,420.2	5,420.2	0	0.60306
8	Pipe	1.0000	0.4619	134,801	126,127	3.000	2.000	-8,674.1	-8,674.1	-8,988	0.03490
9	Pipe	0.5801	0.2679	126,192	124,918	3.000	3.000	1,273.8	1,273.8	0	0.14172
10	Pipe	1.4199	0.6559	127,903	125,676	3.000	3.000	2,227.2	2,227.2	0	0.24780
11	Pipe	1.0000	0.4619	134,449	125,775	3.000	2.000	-8,674.1	-8,674.1	-8,988	0.03490
12	Pipe	0.4199	0.1940	125,856	124,934	3.000	3.000	922.2	922.2	0	0.10260
13	Pipe	1.0000	0.4619	133,527	124,853	3.000	2.000	-8,674.1	-8,674.1	-8,988	0.03490

Pipe	P Static In (Pascals)	P Static Out (Pascals)	P Stag. In (Pascals)	P Stag. Out (Pascals)	dP Static Friction Total (Pascals)	Length (meters)	dP Stag. Total (Pascals)
1	13,482	48,441	140,041	175,000	-34,959.0	0.5000	-34,959.0
2	172,556	133,247	175,000	135,692	12,344.8	6.0000	39,308.2
3	135,119	127,528	135,692	128,100	7,591.5	10.0000	7,591.5
4	128,003	136,677	128,100	136,774	313.7	1.0000	-8,674.1
5	135,041	130,994	135,692	131,645	4,046.9	5.0000	4,046.9
6	131,547	140,221	131,645	140,319	313.7	1.0000	-8,674.1
7	131,401	125,981	131,645	126,225	5,420.2	10.0000	5,420.2
8	126,127	134,801	126,225	134,899	313.7	1.0000	-8,674.1
9	126,192	124,918	126,225	124,951	1,273.8	7.0000	1,273.8
10	127,903	125,676	128,100	125,873	2,227.2	5.0000	2,227.2
11	125,775	134,449	125,873	134,547	313.7	1.0000	-8,674.1
12	125,856	124,934	125,873	124,951	922.2	7.0000	922.2
13	124,853	133,527	124,951	133,625	313.7	1.0000	-8,674.1

Figure 12. Initial piping network data from AFT Fathom.

Modified Piping Network AFT Fathom Data

Pipe	Name	Vol. Flow Rate (liter/sec)	Velocity (meters/sec)	P Static Max (Pascals)	P Static Min (Pascals)	Elevation Inlet (meters)	Elevation Outlet (meters)	dP Stag. Total (Pascals)	dP Static Total (Pascals)	dP Gravity (Pascals)
1	Pipe	-35.97774	-16.61865	48,441	13,482	0.000	0.000	-34,958.96	-34,958.96	0
2	Pipe	5.00000	2.30957	172,556	133,247	0.000	3.000	39,308.16	39,308.16	26,963
4	Pipe	1.00000	0.46191	137,675	129,001	3.000	2.000	-8,674.09	-8,674.09	-8,988
5	Pipe	2.35937	1.08983	135,148	131,447	3.000	3.000	3,700.71	3,700.71	0
6	Pipe	1.00000	0.46191	140,567	131,893	3.000	2.000	-8,674.09	-8,674.09	-8,988
8	Pipe	1.00000	0.46191	136,254	127,580	3.000	2.000	-8,674.09	-8,674.09	-8,988
10	Pipe	0.56253	0.25984	129,068	128,186	3.000	3.000	882.35	882.35	0
11	Pipe	1.00000	0.46191	136,793	128,119	3.000	2.000	-8,674.09	-8,674.09	-8,988
13	Pipe	1.00000	0.46191	135,405	126,731	3.000	2.000	-8,674.09	-8,674.09	-8,988
X14	Pipe	0.00000	0.00000	126,829	0	3.000	0.000	-26,963.39	-26,963.39	-26,963
15	Pipe	2.64063	1.21975	135,010	130,868	3.000	3.000	4,141.88	4,141.88	0
16	Pipe	1.56253	0.72176	131,311	128,860	3.000	3.000	2,450.87	2,450.87	0
17	Pipe	1.07810	0.49799	131,436	129,745	3.000	3.000	1,691.02	1,691.02	0
18	Pipe	1.35937	0.62791	131,810	129,678	3.000	3.000	2,132.19	2,132.19	0
19	Pipe	1.04698	0.48361	129,752	128,110	3.000	3.000	1,642.20	1,642.20	0
20	Pipe	1.39049	0.64229	129,670	127,489	3.000	3.000	2,181.01	2,181.01	0
21	Pipe	0.60951	0.28154	128,180	127,224	3.000	3.000	956.03	956.03	0
22	Pipe	0.39049	0.18037	127,663	127,296	3.000	3.000	367.49	367.49	0
23	Pipe	0.07925	0.03660	127,310	127,260	3.000	3.000	49.72	49.72	0
24	Pipe	0.31124	0.14377	127,301	126,819	3.000	3.000	481.86	481.86	0
25	Pipe	0.68876	0.31815	127,214	126,782	3.000	3.000	432.13	432.13	0

Pipe	dH (meters)	P Static In (Pascals)	P Static Out (Pascals)	P Stag. In (Pascals)	P Stag. Out (Pascals)	dP Static Friction Total (Pascals)	Length (meters)	dP Stag. Total (Pascals)
1	-3.889603	13,482	48,441	140,041	175,000	-34,958.96	0.5000	-34,958.96
2	1.373503	172,556	133,247	175,000	135,692	12,344.77	6.0000	39,308.16
4	0.034903	129,001	137,675	129,099	137,773	313.70	1.0000	-8,674.09
5	0.411748	135,148	131,447	135,692	131,991	3,700.71	5.0000	3,700.71
6	0.034903	131,893	140,567	131,991	140,665	313.70	1.0000	-8,674.09
8	0.034903	127,580	136,254	127,678	136,352	313.70	1.0000	-8,674.09
10	0.098172	129,068	128,186	129,099	128,217	882.35	5.0000	882.35
11	0.034903	128,119	136,793	128,217	136,891	313.70	1.0000	-8,674.09
13	0.034903	126,731	135,405	126,829	135,503	313.70	1.0000	-8,674.09
X14	0.000000	126,829	0	126,829	0	0.00	22.0000	-26,963.39
15	0.460834	135,010	130,868	135,692	131,550	4,141.88	5.0000	4,141.88
16	0.272688	131,311	128,860	131,550	129,099	2,450.87	5.0000	2,450.87
17	0.188146	131,436	129,745	131,550	129,859	1,691.02	5.0000	1,691.02
18	0.237232	131,810	129,678	131,991	129,859	2,132.19	5.0000	2,132.19
19	0.182714	129,752	128,110	129,859	128,217	1,642.20	5.0000	1,642.20
20	0.242663	129,670	127,489	129,859	127,678	2,181.01	5.0000	2,181.01
21	0.106370	128,180	127,224	128,217	127,261	956.03	5.0000	956.03
22	0.040888	127,663	127,296	127,678	127,310	367.49	3.0000	367.49
23	0.005532	127,310	127,260	127,310	127,261	49.72	2.0000	49.72
24	0.053612	127,301	126,819	127,310	126,829	481.86	4.0000	481.86
25	0.048080	127,214	126,782	127,261	126,829	432.13	2.0000	432.13

Figure 13. Modified piping network data from AFT Fathom.

Suggested Improvements Piping Network AFT Fathom Data

Pipe	Name	Vol. Flow Rate (liter/sec)	Velocity (meters/sec)	P Static Max (Pascals)	P Static Min (Pascals)	Elevation Inlet (meters)	Elevation Outlet (meters)	dP Stag. Total (Pascals)	dP Static Total (Pascals)	dP Gravity (Pascals)	dH (meters)
1	Pipe	-35.978	-16.6187	48,440	13,482	0.000	0.000	-34,959	-34,959	0	-3.88958
2	Pipe	5.000	2.3096	172,556	136,385	0.000	3.000	36,171	36,171	26,963	1.02447
4	Pipe	2.000	0.9238	127,458	124,321	3.000	3.000	3,137	3,137	0	0.34903
5	Pipe	1.000	0.4619	147,405	138,731	3.000	2.000	-8,674	-8,674	-8,988	0.03490
10	Pipe	1.000	0.4619	136,426	127,751	3.000	2.000	-8,674	-8,674	-8,988	0.03490
X14	Pipe	0.000	0.0000	123,144	0	3.000	0.000	-26,963	-26,963	-26,963	0.00000
15	Pipe	4.000	1.8477	137,264	130,990	3.000	3.000	6,274	6,274	0	0.69807
16	Pipe	3.000	1.3857	131,675	126,969	3.000	3.000	4,706	4,706	0	0.52355
17	Pipe	1.000	0.4619	141,131	132,457	3.000	2.000	-8,674	-8,674	-8,988	0.03490
18	Pipe	1.000	0.4619	133,289	124,614	3.000	2.000	-8,674	-8,674	-8,988	0.03490
19	Pipe	1.000	0.4619	124,614	123,046	3.000	3.000	1,569	1,569	0	0.17452
20	Pipe	1.000	0.4619	131,720	123,046	3.000	2.000	-8,674	-8,674	-8,988	0.03490

Pipe	P Static In (Pascals)	P Static Out (Pascals)	P Stag. In (Pascals)	P Stag. Out (Pascals)	dP Static Friction Total (Pascals)	Length (meters)	dP Stag. Total (Pascals)
1	13,482	48,440	140,041	175,000	-34,958.7	0.5000	-34,959
2	172,556	136,385	175,000	138,829	9,207.7	4.0000	36,171
4	127,458	124,321	127,849	124,712	3,137.0	5.0000	3,137
5	138,731	147,405	138,829	147,503	313.7	1.0000	-8,674
10	127,751	136,426	127,849	136,523	313.7	1.0000	-8,674
X14	123,144	0	123,144	0	0.0	22.0000	-26,963
15	137,264	130,990	138,829	132,555	6,274.1	5.0000	6,274
16	131,675	126,969	132,555	127,849	4,705.6	5.0000	4,706
17	132,457	141,131	132,555	141,229	313.7	1.0000	-8,674
18	124,614	133,289	124,712	133,386	313.7	1.0000	-8,674
19	124,614	123,046	124,712	123,144	1,568.5	5.0000	1,569
20	123,046	131,720	123,144	131,818	313.7	1.0000	-8,674

Figure 14. Suggested piping network data from AFT Fathom.

Heat Exchanger Design

Fluid Temperatures

$T_i := 45\,°C$

$T_o := 35\,°C$

$t_i := 25\,°C$

Fluid Properties

The major component of solvent based ink is Soy Bean Oil. The group was only able to find a few of the properties of soy bean oil, which were only available at 20C. Since the properties of soy bean oil are very close to those of engine oil, the group used engine oil at 20C to estimate the missing properties.

Ink Properties (@20C)

Cooling Water Properties (@25C)

$$\rho_I := 920\,\frac{kg}{m^3}$$

$$\rho_W := 997.0\,\frac{kg}{m^3}$$

$$\mu_W := 8.9011\cdot10^{-4}\,Pa\cdot s$$

$$\nu_I := 61\cdot10^{-6}\cdot\frac{m^2}{s}$$

$$\nu_W :=$$

$$\mu_I := \rho_I\cdot\nu_I = 0.056\cdot Pa\cdot s$$

$$k_W := 0.60715\,\frac{W}{m\cdot K}$$

$$k_I := 0.145\,\frac{W}{m\cdot K}$$

$$C_{p\_W} := 4181.6\,\frac{J}{kg\cdot K}$$

$$C_{p\_I} := 1876\,\frac{J}{kg\cdot K}$$

$$Pr_I := 10400$$

$$Pr_W := 6.35$$

Fluid Flow Rates

$$m_I := \left(0.005\cdot\frac{m^3}{s}\right)\cdot\rho_I = 4.6\,\frac{kg}{s}$$

$$m_W := 16\,\frac{kg}{s}$$

Solving for Cooling Water Exit Temperature

$$t_o := t_i + \frac{m_I\cdot C_{p\_I}\cdot\left(T_i - T_o\right)}{m_W\cdot C_{p\_W}} = 26.29\cdot{}^\circ C$$

Power Transfered Between Fluids

$$Q := m_I\cdot C_{p\_I}\cdot\left(T_i - T_o\right) = 86.296\cdot kW$$

Since power transfer is on the order of kW there is no need for a shell-tube or plate and frame heat exchanger.

Use Double Pipe Heat Exchanger.

$$Q := m_W\cdot C_{p\_W}\cdot\left(t_o - t_i\right) = 86.296\cdot kW$$

Calculation of Log Mean Temperature Difference

Using Counterflow Design

$$\Delta T_1 := T_i - t_o = 18.71\,K$$

$$\Delta T_2 := T_o - t_i = 10\cdot K$$

$$\Delta T_{lm} := \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} = 13.903 \cdot K$$

Calculation of Required Overall Heat Transfer Coefficient

$$UA := \frac{Q}{\Delta T_{lm}} = 6.207 \times 10^3 \cdot \frac{W}{K}$$

Cooling Water flowing in outer pipe (annular space).

Economic Velocity Range for Water: 1.4-2.8 m/s

Use Economic Velocity of Linseed Oil for Ink (**since densities are approx the same**): 1.5-3.0 m/s

Heat Exchanger Pipe Properties

300 Series Stainless Steel

$\varepsilon := 0.000015cm$

Outer Pipe (5 Sched 40)

$d_{o\_W} := 14.13cm$

$d_{i\_W} := 12.82cm$

$A_{f\_O} := 129.10cm^2$

$$\frac{\varepsilon}{d_{i\_W}} = 1.17 \times 10^{-6}$$

Inner Pipe (2 Sched 40)

$d_{o\_I} := 6.034cm$

$d_{i\_I} := 5.252cm$

$A_{f\_I} := 21.66cm^2$

$$A_{o\_I} := \pi \cdot \frac{d_{o\_I}^2}{4}$$

$$\frac{\varepsilon}{d_{i\_I}} = 2.856 \times 10^{-6}$$

Calculation of Flow Area for Water

$$A_{f\_W} := A_{f\_O} - A_{o\_I} = 100.504 \cdot cm^2$$

Check Velocities of Fluids

$$V_I := \frac{m_I}{\rho_I \cdot A_{f\_I}} = 2.308 \frac{m}{s}$$

$$V_W := \frac{m_W}{\rho_W \cdot A_{f\_W}} = 1.597 \frac{m}{s}$$

Fluid Velocites are within the Economic Ranges

Calculation of Hydraulic and Effective Diameters

$P_{wet} := \pi \left(d_{i\_W} + d_{o\_I}\right) = 59.232 \cdot cm$

$P_{heat} := \pi \cdot d_{o\_I} = 18.956 \cdot cm$

$$D_h := \frac{4\cdot A_{f\_W}}{P_{wet}} = 6.787\cdot cm$$

$$D_e := \frac{4\cdot A_{f\_W}}{P_{heat}} = 21.208\cdot cm$$

Calculation of Reynold's Number

$$Re_{Dh\_W} := \frac{\rho_W \cdot V_W \cdot D_h}{\mu_W} = 1.214\times 10^5$$

$$Re_I := \frac{\rho_I \cdot V_I \cdot d_{i\_I}}{\mu_I} = 1.987\times 10^3$$

$$Re_{De\_W} := \frac{\rho_W \cdot V_W \cdot D_e}{\mu_W} = 3.793\times 10^5$$

Calculation of Friction Factors for Ink Flow and Cooling Water Flow using Chen Correlation

$$f_I := \left[-2\cdot\log\left[\frac{\varepsilon}{3.7065 d_{i\_I}} - \frac{5.0452}{Re_I}\cdot\log\left[\frac{1}{2.8257}\cdot\left(\frac{\varepsilon}{d_{i\_I}}\right)^{1.1098} + \frac{5.8506}{Re_I^{0.8981}}\right]\right]\right]^{-2} = 0.049$$

Ink flow is laminar since Reynolds Number is <2200

$$f_I := \frac{64}{Re_I} = 0.032$$

$$f_W := \left[-2\cdot\log\left[\frac{\varepsilon}{3.7065 D_h} - \frac{5.0452}{Re_{Dh\_W}}\cdot\log\left[\frac{1}{2.8257}\cdot\left(\frac{\varepsilon}{D_h}\right)^{1.1098} + \frac{5.8506}{Re_{Dh\_W}^{0.8981}}\right]\right]\right]^{-2} = 0.017$$

Calculation of Nusselt Numbers for Ink and Cooling Water

$$Nu_I := 0.023 Re_I^{0.8}\cdot Pr_I^{0.3} = 160.503$$

$$Nu_W := 0.023 Re_{De\_W}^{0.8}\cdot Pr_W^{0.4} = 1.4\times 10^3$$

Calculation of Individual and Net Heat Transfer Coefficients

Choose Heat Exchanger Length:

$$h_I := \frac{Nu_I\cdot k_I}{d_{i\_I}} = 443.125\cdot\frac{W}{m^2 K}$$

$$h_W := \frac{Nu_W\cdot k_W}{D_e} = 4.007\times 10^3\cdot\frac{W}{m^2 K}$$

$$U_o := \frac{1}{\frac{1}{h_I} + \frac{1}{h_W}} = 399.001\cdot\frac{W}{m^2\cdot K}$$

Fouling Factors of Ink and Cooling Water

Use value for Engine Oil in place of Soy Bean Oil. Assume thin wall of inner tube creates no conductive resistance.

$$R_{f\_I} := 0.0002\frac{m^2\cdot K}{W}$$

$$R_{f\_W} := 0.0004\,\frac{m^2 K}{W}$$

Calculation of Total Heat Exchanger Transfer Coefficient

$$U := \frac{1}{\frac{1}{U_o} + R_{f\_W} + R_{f\_I}} = 321.931 \cdot \frac{W}{m^2 K}$$

$$A_0 := \frac{Q}{U \cdot \Delta T_{lm}} = 19.28\,m^2$$

$$L_0 := \frac{A_0}{\pi \cdot D_e} = 28.938\,m$$

Required Length of HX

Calculation of Pressure Drop Across Heat Exchanger

$$\Delta p_I := \frac{f_I \cdot L_0}{d_{i\_I}} \cdot \frac{\rho_I \cdot V_I^2}{2} = 43.491 \cdot kPa$$

$$\Delta p_W := \left(\frac{f_W \cdot L_0}{D_h} + 1 \right) \cdot \frac{\rho_W \cdot V_W^2}{2} = 10.653 \cdot kPa$$

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