Quality Assurance in solar thermal heating and cooling technology

Keeping track with recent and upcoming developments

Summary report

Pressure drop over a solar flat plate collector using various heat transfer fluids

SP – Technical Research Institute of Sweden

Peter Kovacs, SP
Martin Persson, SP
Peter Wahlgren, SP
Sara Jensen, SP

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1 Introduction

The pressure drop over a solar collector is an important parameter for system designers. It is becoming increasingly important as the focus on energy efficiency is getting stronger and the designer should minimize the energy needed for pumping yet maintaining flow rates that allows the collectors to operate efficiently. Pressure drop data is a mandatory part of the collector manufacturers' documentation but the measurement of pressure drop is not a compulsory part of the standard. I.e. the manufacturer can perform these measurements by himself. The collector test standard EN 12975 gives the following directives for these measurements:

"The fluid used in the collector for the test shall be water or a mixture water: glycol (60:40), or a mixture recommended by the manufacturer. The temperature of the fluid shall be (20 ± 2) °C."

From this it can be understood that there is some confusion among designers when trying to compare different collectors' pressure drop data. Furthermore, it would be very useful to have a correlation enabling pressure drop data derived using one fluid (preferably water) to be re-calculated to any other water/glycol mixture with known properties.

This document aims at explaining the theory behind the pressure drop over a solar collector and how the pressure drop is related to various heat transfer media. It should be seen as a first attempt to correlate pressure drop data for different media. Included in the study is a series of laboratory experiments where the pressure drop over a solar flat plate collector has been measured with various mixtures of water and glycol at various temperatures.

2 Theory

The pressure drop over the collector is given by Δp .
Δp is calculated from the following equation:

$$\Delta p = \underbrace{f\frac{\rho V^2}{2}\frac{\Delta l}{d}}_{1} + \underbrace{k\frac{\rho V^2}{2}}_{2} \quad (3) \quad (\text{White}, 2003).$$

Where:
f [-], is the friction factor given in the moody diagram as a function of the Reynolds number, the wall roughness, ε and the diameter of the tube, d as follow:

$$\frac{1}{f^{1/2}} = -2.0 \log\left(\frac{\varepsilon/d}{3.7} + \frac{2.51}{Re_d f^{1/2}}\right) \ (4)\ (\text{White}, 2003).$$

ρ [kg/m^3], is the density of the heat transfer media

V [m/s], is the velocity of the heat transfer media

Δl **[m]** is the length of the tube

d [m], is the diameter of the tube

k [-], is the loss coefficient due to entrance effects, exit effects, bends, elbows, valves, etc.

The loss coefficient k [-] is often taken from tables derived from tests or calculated with formulas that are independent of the density and kinematic viscosity of the heat transfer fluid.

3 Calculation of the Reynolds number for the solar collector

By using equation (5) it is possible to determine if the flow in the solar collector is laminar or turbulent. For fully developed flow in a pipe laminar flow occurs when Re below 2300 and turbulent occurs when the Reynolds number is over 4000. In the interval between 2300 and 4000 the flow could be either laminar or turbulent. This is the so called transition region.

$$Re = \frac{\rho V L}{\mu} = \frac{VL}{\nu} (5) \ (\text{White}, 2003).$$

Where:

ρ [kg/m^3], is the density of the fluid

V [m/s], is the velocity of the fluid

μ [kg/ms], is the dynamic viscosity of the fluid

ν [m^2/s], is the kinematic viscosity of the fluid

L [m], is the characteristic length. For flow in a pipe it is defined as D_H, hydraulic diameter

The Reynolds numbers have been calculated by using equation (5). The velocities used are the ones in the smaller pipes where the inner diameter is 0,0084 m, see Figure 2, which have lower velocities of the fluid and are therefore the most critical pipe where laminar flow could occur. The velocity in the smaller pipes is assumed to be the same in all 20 pipes. **Table 1** presents these results.

Table 1 Calculated Reynolds numbers for water and different glycol mixtures and temperatures for dn=0,0084 m

	T [°C]	μ [kg/ms]	ρ [kg/m^3]	v [m^2/s]	Re (at 1 m^3/h)	Re (at 2 m^3/h)	Re (at 3 m^3/h)
Water 100%	10	1.27E-03	1000	1.27E-06	1979	3958	5937
	20	9.77E-04	998	9.79E-07	2560	5120	7680
	40	6.35E-04	992	6.40E-07	3915	7830	11746
	60	4.54E-04	983	4.62E-07	5426	10853	16279
Glycol 30%	10	3.04E-03	1040	2.92E-06	857	1715	2572
	20	2.17E-03	1040	2.09E-06	1201	2402	3603
	40	1.27E-03	1030	1.23E-06	2033	4065	6098
	60	8.50E-04	1010	8.42E-07	2978	5956	8934
Glycol 50%	10	5.11E-03	1060	4.82E-06	520	1040	1560
	20	3.87E-03	1060	3.65E-06	686	1373	2059
	40	2.24E-03	1040	2.15E-06	1164	2327	3491
	60	1.35E-03	1030	1.31E-06	1912	3824	5736

At a flow rate of 1 m^3/h water reaches over the critical Reynolds number of 2300 for temperatures between 20°C and 60°C. To reach turbulent flow for 10°C water the flow rate needs to be higher than 1 m^3/h. The 50% glycol mixture is in the laminar zone for the flow rate of 1 m^3/h and the 30% glycol mixture only reaches the turbulent zone at the temperature of 60°C.

4 Turbulent flow

High Reynolds numbers

From the moody chart one can see that for high Reynolds numbers the friction factor, f is constant. This means that for high Reynolds numbers the contribution to the pressure drop over the collector is direct proportional to the change in the density of the heat transfer media given that the geometry and the velocity is constant. Hence for high Reynolds numbers, when the friction factor is constant, the pressure drop for various heat transfer media can be recalculated with the change in density for various heat transfer media. This is valid for Reynolds numbers > $1x10^6$. From Table 1 it can be seen that Reynolds numbers > $1x10^6$ never occurs for the tested collector and this case is therefore not interesting.

Lower Reynolds numbers

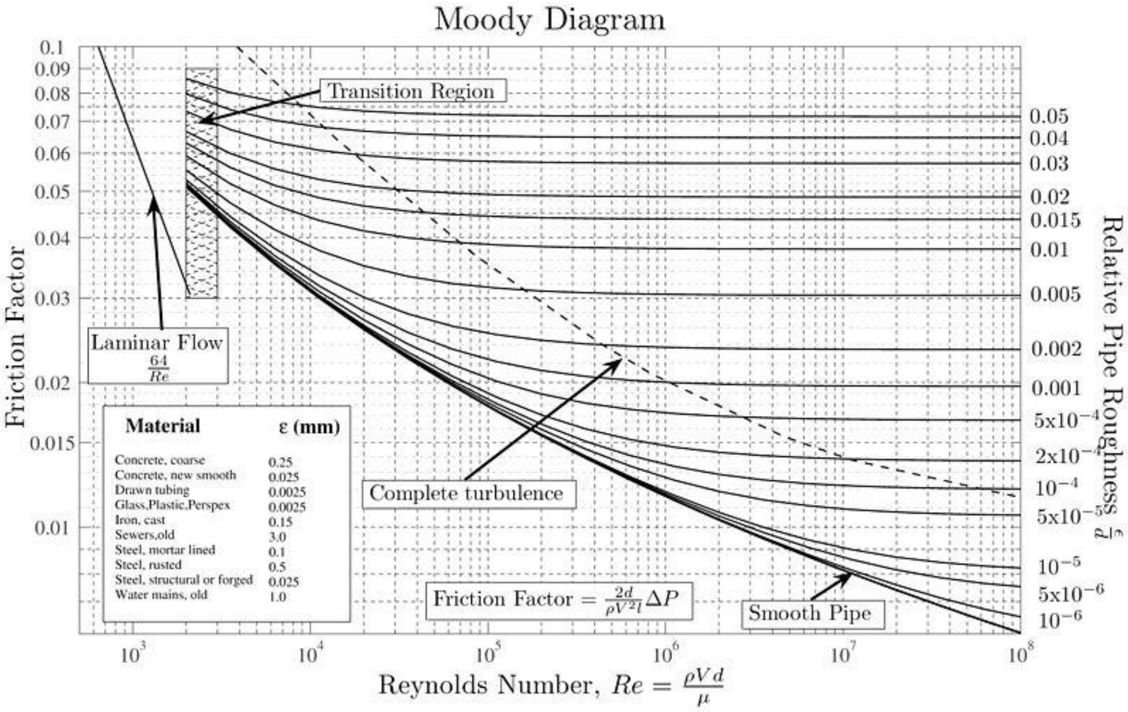
For the case with low Reynolds numbers but still in the turbulent or transition region the contribution to the pressure drop from term 1 in equation (3) is dependent on the Reynolds number, the wall roughness, ε and the diameter of the tube, d, and this relationship is given in equation (4). From equation (4) one can see that only the Reynolds number will change with varying heat transfer media. The variation in the Reynolds number will be dependent on the kinematic viscosity. Then in order to recalculate the pressure drop between various heat transfer media one needs to know the relationship between term 1 and term 2 in equation (3) and the kinematic viscosity in order to determine the Reynolds number for the various heat transfer media and then use equation (4) to determine the new friction factor, f.

Reynolds numbers in this region is the normal case when using the recommended flow for this type of collector. It is then interesting to assess how much the change in kinematic viscosity influences the friction factor, f, and how much that changes the pressure drop. For the concerned heat transfer media it is also interesting to investigate how the kinematic viscosity varies with the temperature.

5 Laminar flow

For laminar flow the friction factor is given by:

$$f = \frac{64}{Re} \quad (6) \quad \text{(White, 2003)}.$$



Material	ε (mm)
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass,Plastic,Perspex	0.0025
Iron, cast	0.15
Sewers,old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

Figure 1 Moody diagram

6 Solar collector data

The solar collector used for the experiment was a large flat plate collector with two branch pipes and 20 parallel stripes. The outer diameter of the branch pipes and the stripes are 35 mm and 10 mm respectively. The general design and the dimensions of the collector used are described in Figure 2.

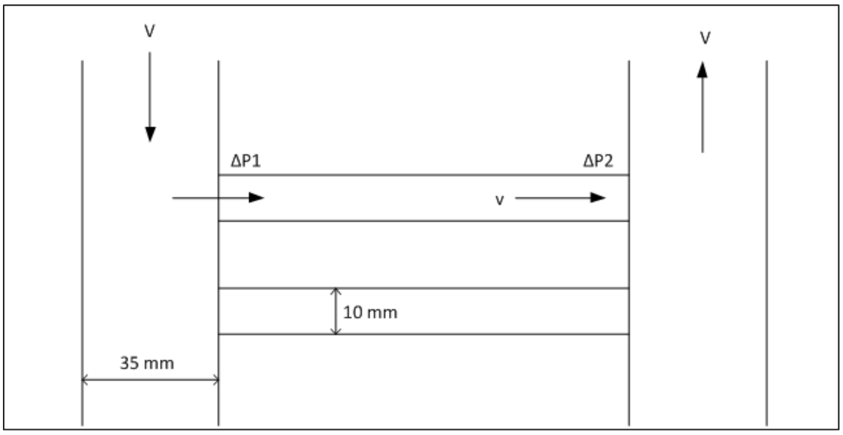


Figure 2 Fundamental sketch of piping design and dimensions of the solar collector

The pressure drop tests have been performed with a flow rate of 1 m^3/h up to 6 m^3/h. Table 1 presents the calculated pipe velocities. “v” corresponds to the velocity in the 10 mm outer diameter pipe and “V” in the 35 mm outer diameter pipe.

Table 1

Total flow over the collector [m^3/h]	V (0,032 m)[m/s]	v (0,0084 m) [m/s]
1	0,35	0,25
2	0,69	0,50
3	1,04	0,75
4	1,38	1,00
5	1,73	1,25
6	2,07	1,50

Calculation of k, the loss coefficient

The flow enters the solar collector in a 35 mm pipe, the pipe then splits into 20 smaller pipes with the diameter of 10 mm. Finally the heat transfer media exits the 10 mm pipes and enters a 35 mm pipe. That means that there are 20 area reduction and 20 area increases that the heat transfer media has to pass through the solar collector. The pressure drop caused by the geometry changes can be calculated by using equation (7). Pressure drop due to entrance and exit effects:

$$\Delta p = \sum k_i \frac{\rho V^2}{2} \quad (7) \text{ (White, 2003).}$$

Where:

ρ [kg/m^3], is the density of the heat transfer media

V [m/s], is the velocity of the heat transfer media

k [-],is the loss coefficient due to entrance effects, exit effects, bends, elbows, valves, etc.

k$_1$ for an area increase is given by the following equation:

$$k_1 = \left(1 - \frac{A1}{A2}\right)^2 \quad (8) \text{ (White, 2003).}$$

Where:
A, is the area of the cross section and $A_1 < A_2$

k$_2$ for a area decrease is given by the following equation:

$$k_2 = \left(\frac{1-\varphi}{\varphi}\right)^2 \quad (9) \text{ (White, 2003).}$$

Where:

φ , is the contraction coefficient and can be found in tables.

By using equation (8) and (9) k is calculated for both the area increase and the decrease:

Area reduction: k_1= 0,44

Area increase: k_2= 0,87

With the loss coefficients determined the pressure drop can be calculated.
Table 3 shows the calculated pressure drop due to entrance and exit effects for 20 pipes.
The calculations have been made using equation (7)

Table 2 Entrance and exit pressure drop for water at 20°C [Pa]

Flow rate **[m³/h]**	Δp, entrance**[Pa]**	Δp, exit**[Pa]**	Δp, (entrance+exit)**[Pa]**	Δp, (entrance+exit)**[mbar]**
1	529	543	1073	10,7
2	2117	2174	4290	42,9
3	4762	4891	9653	96,5
4	8466	8695	17161	171,6
5	13228	13586	26814	268,1
6	19049	19564	38613	386,1

Comparison between water and different glycol concentrations at 10°C, 40°C and 60°C
The pressure drop charts have been produced from measurement data from the SP laboratory. In the following three charts the blue line represents water, the red line is 10% glycol, the green 30% glycol mixture and the purple represents a 50% glycol mixture. The charts represents the same pressure drop measurements but with different temperatures and glycol mixtures.

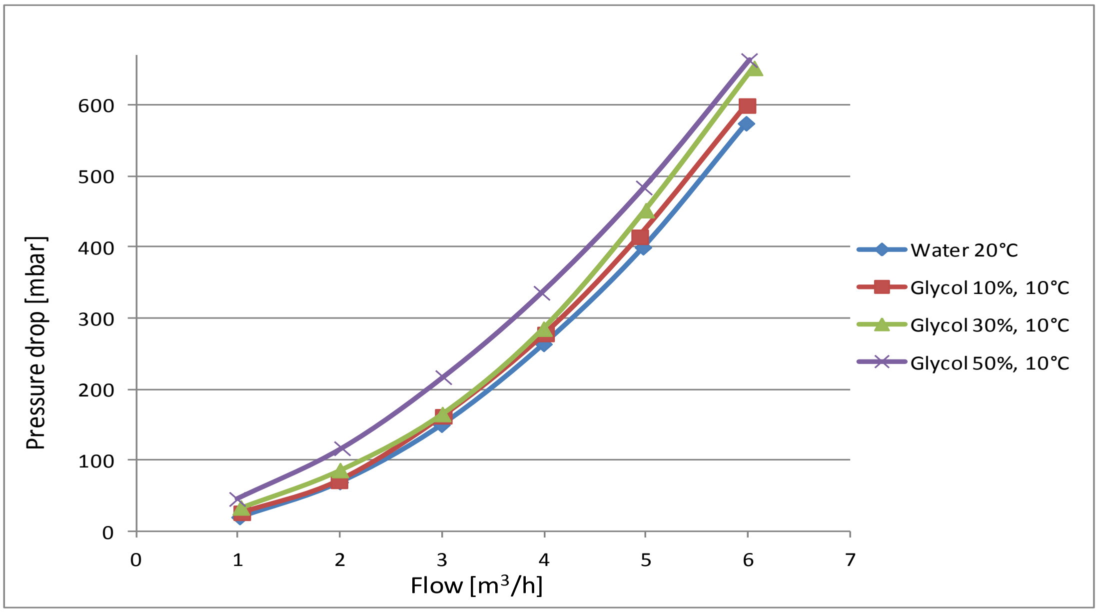


Figure 1 Pressure drop comparison between water at 20°C and 10%, 30%, 50% glycol at 10°C

Water and glycol mixtures of 10% and 30% show small differences all the way up to 6 m³/h. Glycol at 50% has a higher pressure loss for all flow rates and has approximately 15% higher pressure drop at the flow rate 6m³/h than water.

Table 3 Pressure drop Difference between glycol mixtures at 10°C and water at 20°C

Flow rate [m³/h]	Glycol 10%, 10°C	Glycol 30%, 10°C	Glycol 50%, 10°C
1	30%	68%	128%
2	2%	24%	69%
3	8%	10%	45%
4	5%	8%	27%
5	4%	13%	21%
6	4%	14%	15%

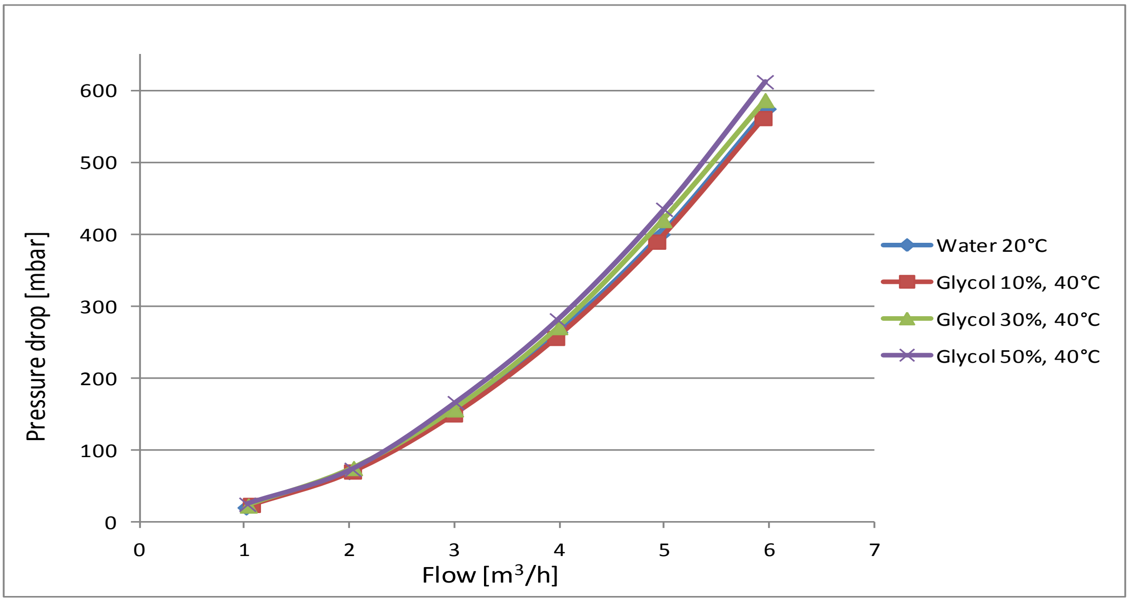


Figure 2 Pressure drop comparison between water at 20°C and 10%, 30%, 50% glycol at 40°C

At a temperature of 40°C the glycol mixtures shows small differences in pressure drop from water at 20°C.

Table 4 Pressure drop Difference between glycol mixtures at 40°C and water at 20°C

Flow rate [m³/h]	Glycol 10%, 40°C	Glycol 30%, 40°C	Glycol 50%, 40°C
1	18%	13%	22%
2	1%	8%	5%
3	0%	4%	10%
4	-3%	3%	6%
5	-3%	5%	9%
6	-2%	2%	7%

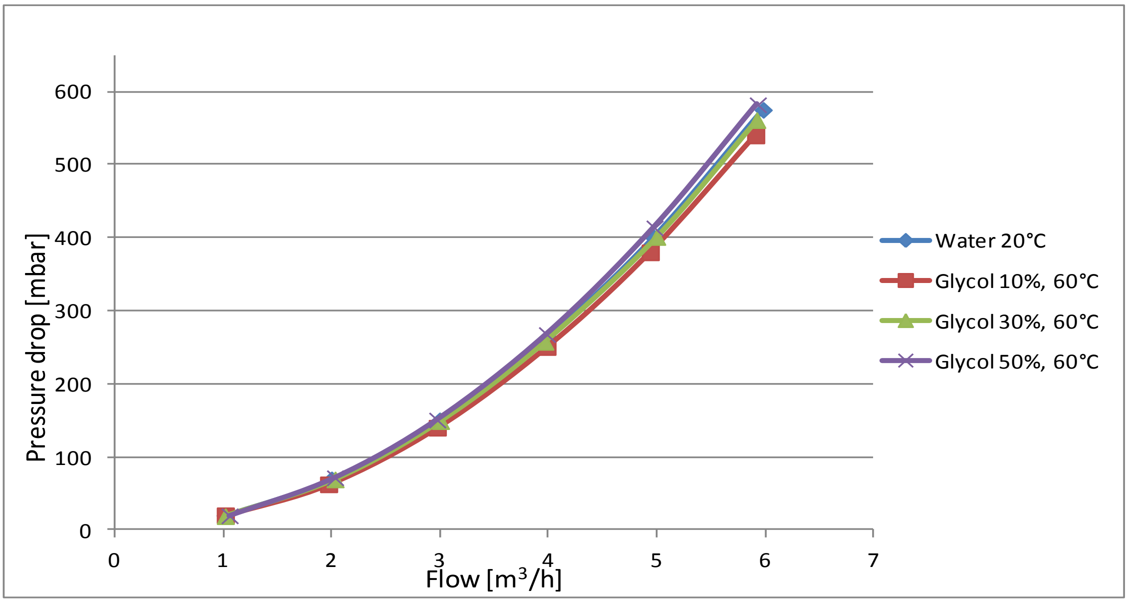


Figure 3 Pressure drop comparison between water at 20°C and 10%, 30%, 50% glycol at 60°C

At a temperature of 60°C the glycol mixtures shows small differences in pressure drop from water at 20°C.

Table 5 Pressure drop Difference between glycol mixtures at 60°C and water at 20°C

Flow rate [m³/h]	Glycol 10%, 60°C	Glycol 30%, 60°C	Glycol 50%, 60°C
1	1%	-6%	-3%
2	-10%	0%	3%
3	-7%	-1%	0%
4	-5%	-2%	1%
5	-5%	0%	3%
6	-6%	-2%	1%

7 Discussion and conclusions

The result presented in Figure 1, Figure 2 and Figure 3 shows that the difference in pressure drop between water and the water-glycol mixture is relatively small at high temperatures and low concentrations of glycol. This is due to that the kinematic viscosity, at high temperatures, is quite similar for the various fluid mixtures tested. It is only at very low temperatures and high concentrations that there is a big difference in pressure drop between water and the water-glycol mixture.

The small difference in pressure drop shown in figure 3 and 4 between water at 20°C and the different glycol mixtures at the temperatures of 40°C and 60°C leads up to the conclusion that a pressure drop test conducted with water at 20°C should be valid for glycol mixtures up to 50% with a working temperature above 40°C for this type of solar collector. The result showed in Figure 2 and Figure 3 shows that it is unnecessary to test the pressure drop with glycol if the temperatures are over 40°C for this type of solar collector.

Although it should be concluded that if the contribution to the pressure drop from area changes and bends is very small in comparison to the pressure drop due to friction losses the difference between various heat transfer fluids will be larger than for the test case if the temperature of the heat transfer fluid is low. For the collector tested here the contribution to the pressure drop from area changes is about 50%-70%. This is quite a big fraction of the losses coming from area changes and to further confirm the results from this assessment other collector designs should be tested.

Further on, from figure 2 the conclusion can be made that even for temperatures as low as 10°C it would be sufficiently good to test the pressure drop with only water if the 10% to 30% glycol mixtures are to be used. For a flow rate of 1 m³/h our calculations show that parts of the piping will have laminar flow if the water temperature is 10°C or lower.
If a glycol mixture of 30 % or 50% is used only the 30% mixture at 60°C will result in a turbulent flow at a flow rate of 1 m³/h.

References

White, Frank M. (2003) Fluid mechanics fifth edition

Appendix

Measurements of the pressure drop have been carried out for water and different concentrations of ethylene glycol. The original results from those tests are presented here.

Test results water

Table 6 shows the pressure drop over the collector with water at 20 °C.

Table 6 Heat transfer media water 100%

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
20,1	1,0	20
20,2	2,0	69,3
20,3	3,0	150,1
20,2	4,0	264
20	5,0	400,3
19,8	6,0	575

Test results glycol 10%

Figure 4 and tables 8-10 show the pressure drop over the collector with 10% glycol at 10°C, 40°C and 60°C.

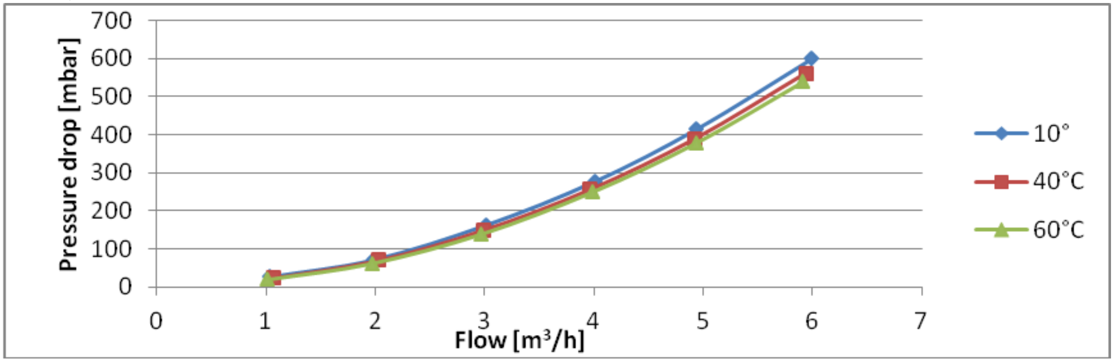


Figure 4 Pressure drop with 10 % glycol

Table 7 Glycol 10%, 10°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
9,7	1,03324	26
10,2	1,987	71
10,2	3,010305	162
10	4,01374	278
10,1	4,937695	415
10,3	5,990805	600

Table 8 Glycol 10%, 40°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
40,2	1,063045	23,5
40,2	2,02674	70
40,2	2,990435	149,5
40	3,964065	256
40	4,92776	390
40,3	5,94113	562

Table 9 Glycol 10%, 60°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
59,9	1,01337	20,2
59,8	1,96713	62,5
60	2,970565	140
60,2	3,983935	250,4
60,4	4,937695	380
60	5,911325	540

Test results glycol 30%

Figure 5 and tables 11 to 13 show the pressure drop over the collector with 30% glycol at 10°C, 40°C and 60°C.

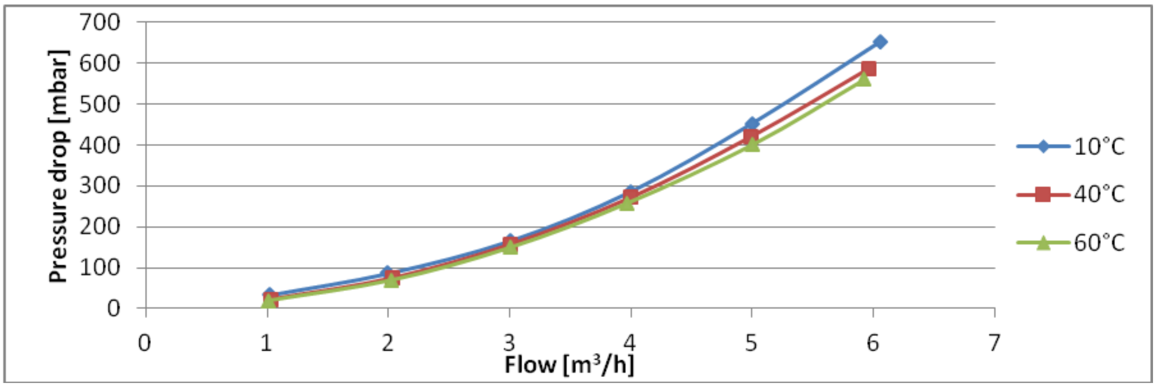


Figure 5 Pressure drop with 30% glycol

Table 10 Glycol 30%, 10°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
9,7	1,02	34
10,1	2,00	86
10,3	3,00	165
10,1	3,99	286
10,1	5,00	453
10,3	6,06	653

Table 11 Glycol 30%, 40°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
40	1,03	23
39,9	2,04	75
39,7	3,00	157
39,6	3,99	271
39,6	4,99	420
40	5,96	587

Table 12 Glycol 30%, 60°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
60	1,01	19
60,2	2,03	69
59,9	3,00	149
59,8	3,96	258
59,6	5,00	401
59,8	5,92	561

Test results glycol 50 %

Figure 6 and tables 14-16 show the pressure drop over the collector with 30% glycol at 10°C, 40°C and 60°C.

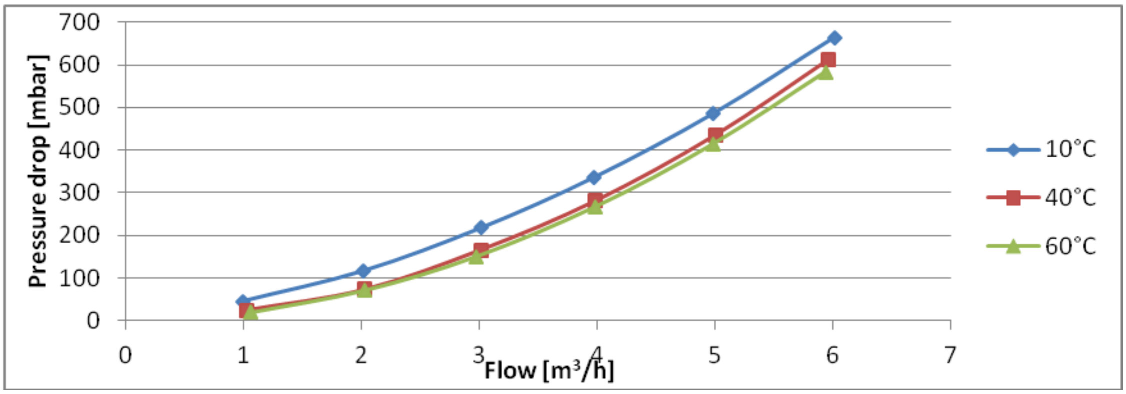


Figure 6 Pressure drop with 50 % glycol

Table 13 Glycol 50%, 10°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
10,4	0,99	46
10,2	2,02	117
9,9	3,01	217
9,7	3,97	336
9,8	4,98	485
10,3	6,01	664

Table 14 Glycol 50%, 40°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
40,4	1,02	24
40,3	2,03	73
40	3,01	166
40,2	3,98	281
40,2	5,00	435
40,5	5,96	613

Table 15 Glycol 50%, 60°C

Temperature [°C]	Flow rate [m³/h]	Pressure drop [mbar]
60	1,05	19
60	2,03	72
59,7	2,97	151
60	3,98	268
60,2	4,98	414
60,3	5,93	582