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Different ethyl alcohol secondary fluids used for GSHP in Europe

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Abstract

The most common secondary fluid used for the borehole heat exchangers in Sweden is aqueous solution of ethyl alcohol (EA). Commercially available ethyl alcohol based fluids in Sweden and other European countries contain various denaturing agents. Ethyl alcohol based secondary fluids in Sweden are distributed as ethyl alcohol concentrate, including up to 12 wt-% denaturing agents in form of propyl alcohol (PA) and n-butyl alcohol (BA). In other European countries, like Switzerland and Finland, the commercial products containing a mixture of methyl ethyl ketone and methyl isobutyl ketone (up to 4.5 vol-%) are used for GSHP application. The chemical character of these denaturing agents can in different ways affect the thermophysical properties. Therefore, the aim of this paper was to investigate the performance of commercially available alcohol blends in Europe in terms of pressure drop and heat transfer in the BHE. The results show that the most commonly used product in Sweden (EA18+PA1.6+BA0.4) presents the best characteristics in terms of higher heat transfer (up to 10 %) and lower pressure drop (up to 2.7 %) among different commercial products found in Europe. Another commercial product used in Switzerland showed second best performance in terms of higher heat transfer (up to 5 %) and lower pressure drop (up to 2 %). Moreover, other products containing higher concentrations of denaturing agents presented the worst performance in terms of lower heat transfer (up to 8 %) and higher pressure drop (up to 1 %) compared to EA20.

Keywords: ground source heat pump; secondary fluid; ethyl alcohol; denaturing agents;

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1. Introduction

Sweden is the European leader in geothermal energy utilization in terms of the installed capacity and extracted thermal energy. It is estimated that there are about 500 000 small and 500 large ground source heat pumps [1]. The dominant type of ground source heat pump (GSHP) systems are shallow low temperature systems ranging from 5 to 10 kW that provide about 23 TWh of heating and cooling. The total installed heating and cooling capacity in Sweden is estimated to be 6.8 GW [2]. The typical Swedish setup consists of one or several vertical borehole heat exchangers (BHE) having a depth between 120 and 300 m. The most commonly used heat exchangers are closed-loop single U-pipes, although double U-pipes are also often used for commercial GSHP systems. The typical pipe size is 40x2.4 mm for single U-pipe and 32x2.0 mm PN10 PE100 for double U-pipes. Moreover, the market for larger shallow GSHP systems for both residential and non-residential buildings has been expanding over the last years [2].Geological Survey of Sweden (SGU) and the Swedish Environmental Protection Agency recommend ethyl alcohol based secondary fluids for GSHP application due to relatively good thermophysical properties and low toxicity [3]. The ethyl alcohol based secondary fluids are usually not exceeding 30 wt-%, corresponding to the freezing point of -20.5 ºC.

European Union regulations strictly define the types and concentrations of denaturing agents added to prevent from drinking of ethyl alcohol based secondary fluids. The most common type of denaturing agents for GSHP application are: propyl alcohol (2-propanol, isopropanol, PA), n-butyl alcohol (n-butanol, BA), methyl ethyl ketone (2-butanone, MEK) and methyl isobutyl ketone (4-methylpentan-2-one, MIBK) [4]. In North America the most common denaturing agents for ethyl alcohol based secondary fluid are methyl alcohol (methanol) (3.76 - 10 wt-%) and pine needle oil (up to 0.5 vol-%) [5-6]. Nevertheless, European commercial products containing ketones and alcohols can be found on American market as well. In Sweden there are only two approved denaturing agents for ethyl alcohol based secondary fluid: propyl alcohol and n-butyl alcohol due to their low toxicity compared to ketones. Both propyl and butyl alcohols occur in nature as the fermentation products and their biodegradation time is up to 28 days. The commercially available ethyl alcohol based secondary fluids in Sweden are normally distributed as 88 - 95 wt-% ethyl alcohol concentrate, including up to 12 wt-% of denaturing agents but no corrosion inhibitors. The most common type of ethyl alcohol product in Sweden contains 8 wt-% propyl alcohol and 2 wt-% n-butyl alcohol. Another less used product on the Swedish market contains 12 wt-% of denaturing agents (10 wt-% propyl alcohol and 2 wt-% n-butyl alcohol) [7].

In other European countries, like Switzerland and Finland, commercial products containing a mixture of two ketones are used for GSHP application. In Switzerland the commercial ethyl alcohol products contain 2 vol-% methyl ethyl ketone and 0.5 vol-% methyl isobutyl ketone [8], whereas in Finland they contain 1.8 vol-% methyl ethyl ketone and 2.7 vol-% methyl isobutyl ketone [9]. Previous results [10-12] showed that presence of propyl alcohol in ethyl alcohol solution improves the thermophysical properties such as specific heat capacity, thermal conductivity and dynamic viscosity, when added in small concentrations. The chemical character of various denaturing agents and concentrations can in different way affect the thermophysical properties. Thus, a comparative study is made to evaluate the performance of different ethyl alcohol based commercial products in Europe in terms of pressure drop and heat transfer in the BHE.

2. Methodology

Four different ethyl alcohol water based solutions with different denaturing agents used in Europe for GSHP application were studied in this article. The total alcohol concentration in all samples was set to be 20 wt-%. Note that ethyl alcohol samples containing ketones have higher total concentrations compared to samples with different alcohol based denaturing agents. The obtained thermophysical properties for different solutions were compared with two reference fluids (deionized water and pure 20 wt-% ethyl alcohol, EA20) to evaluate the measurement errors. Table 1 summarizes the chemical composition of different ethyl alcohols solutions.

Table 1. Ethyl alcohol samples with different denaturing agents.

Sample	Conc. of ethyl alcohol (wt-%)	Conc. of denaturing agent 1 (%)	Conc. of denaturing agent 2 (%)
EA20	20.0	0	0
EA18+PA1.6+BA0.4	18.0 (22.07 vol-%)	propyl alcohol - 1.6 wt-%	n-butyl alcohol - 0.4 wt-%
EA17.5+PA2+BA0.5	17.5 (21.47 vol-%)	propyl alcohol - 2.0 wt-%	n-butyl alcohol - 0.5 wt-%
EA20+MEK1.8+MIBK2.7	20.0 (24.54 vol-%)	methyl ethyl ketone – 1.8 vol-%	methyl isobutyl ketone – 2.7 vol-%
EA20+MEK2+MIBK0.5	20.0 (24.54 vol-%)	methyl ethyl ketone – 2.0 vol-%	methyl isobutyl ketone – 0.5 vol-%

2.1 Freezing point

The freezing point was measured using a microDSC evo7 from Setaram Instrumentation. Differential Scanning Calorimetry (DSC) method is a thermoanalytical technique in which the difference in the amount of heat required to increase the temperature of sample and reference is measured simultaneously. First the water sample was tested in order to define the testing parameters, using continuous standard zone mode at four different heating and cooling scanning rates: 0.025; 0.05; 0.1 and 0.15 $K \cdot min^{-1}$. The difference in results for the three first scanning rates was only 0.01 K, thus, the scanning rate of 0.1 $K \cdot min^{-1}$ was chosen. The sample volume was always kept constant (750µl) and each test was repeated twice. The accuracy of temperature measurements for the instrument according to the manufacturer is set to be ± 0.1 K.

2.2 Density

The density measurements were performed using pycnometers. The pycnometer is a glass bottle with a stopper having a capillary tube through it. By knowing the total volume and by measuring the mass of empty as well as of full pycnometer with Mettler Toledo high accuracy analytical balance (accuracy of ± 0.0001 g), it was possible to determine the density of solutions at 20 °C. The accuracy of density measurement at 20 °C using calibrated pycnometer (volume 25.131 cm^3) is of ± 0.2 %. Later, all results can be fitted to a function to extrapolate values in the desired range between -13 ºC and 30 ºC with the help of literature values.

2.3 Dynamic viscosity

Brookfield rotational viscometer DV-II Pro with special low viscosity adapter (UL-adapter) was used to perform dynamic viscosity measurements in the temperature range between -10 and 30 °C with the instrument accuracy of ± 1 %. The working principle of the rotational viscometer is to drive a spindle immersed in the test fluid through a calibrated spring. The viscous drag of the fluid against the spindle is later measured by the spring deflection. All measurements were done using the same UL-adapter and spindle to reduce the uncertainty of measurements. The dynamic viscosity result was obtained as the slope of shear stress versus shear rate function for the range of torque between 10 and 90 %.

2.4 Thermal conductivity

Thermal conductivity measurements were performed using Transient Plane Source (TPS) method by means of Hot Disk Thermal Constants Analyser TPS-2500S having the accuracy of ± 2 %. Hot Disk sensor consisted of an electrically conducting pattern in the shape of a double spiral, which had been etched out of a thin metal foil. By passing an electrical current high enough to increase the temperature of sensor between a fraction of a degree up to several degrees, and at the same time recording the resistance (temperature) increase as a function of time, the sensor is used both as a heat source and as a dynamic temperature sensor. Kapton sensor 7577 with radius 2.001 mm was chosen and tests for a given temperature were repeated three times at different measuring time (2 - 3 s) and output power (20 - 30 mW). All samples had the same volume of 10 ml and were tested in the temperature range between -10 and 30 °C.

2.5 Specific heat capacity

The specific heat capacity and freezing point were measured using a microDSC evo7 from Setaram Instrumentation. The specific heat capacity tests were performed in c_p continuous mode with heating scanning rate of 0.05 K·min^{-1} in temperature range between -10 and 30 °C. The accuracy of specific heat capacity measurements is ± 1 %. The sample volume was always kept constant (750 µl).

2.6 Implications for a borehole heat exchanger (BHE)

The head loss is calculated per meter of pipe using eq.(1):

$$\Delta H' = f\frac{\bar{u}^2}{2\cdot g\cdot D_h} \quad (1)$$

For the turbulent flows, the friction factor, *f*, is calculated for smooth pipes using eq.(2), while the Poiseuille's law presented as eq.(3) is used for laminar flow conditions.

$$\text{for } Re > 2300,\ f = (0{,}79\cdot\ln(Re) - 1{,}64)^{-2} \quad (2)$$

$$\text{for } Re \leq 2300,\ f = \frac{64}{\mathrm{Re}} \quad (3)$$

The measured and calculated pressure drops using this method are similar, meaning that neglecting roughness is a good assumption in PE pipes [14]. Moreover, for the Reynolds number, Re, lower than 10^4 and for the relative roughness, ε, lower than $8\cdot10^{-4}$, the absolute roughness will have a limited influence on the friction factor. The hydrodynamic entry length is estimated to be about $0.05\cdot Re\cdot D_h$ for laminar flows [15] and of maximum $60\cdot D_h$ for turbulent flows [16], which results in negligible value for the entry length compared to common U-pipe length. The Reynolds number, Re, Prandtl number, Pr, and Nusselt number, Nu, are presented as eq.(4-6) respectively:

$$Re = \frac{\bar{u}\cdot D_h\cdot\rho}{\mu} \quad (4)$$

$$Pr = \frac{\mu\cdot c_p}{k} \quad (5)$$

$$Nu = \frac{h\cdot D_h}{k} \quad (6)$$

Thus, the convection heat transfer coefficient, h, can be calculated by using the Nusselt number. Nusselt number is estimated using Gnielinski correlation [17] denoted as eq.(7) for turbulent flows ($3000 \leq Re \leq 5\cdot10^6$).

$$Nu = \frac{(f/8)\ (Re-1000)Pr}{1+12{,}7\cdot(f/8)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}}-1\right)} \quad (7)$$

In case of the laminar flow conditions in BHE, the thermal entry region is usually significant as compared to the total pipe length because of increasing values of the Prandtl number with the decreasing temperatures. The flow is thermally fully-developed when the Graetz number, Gz, reaches 20 [16]. The Graetz number is expressed using eq.(8) as:

$$Gz = Re \cdot Pr \cdot \left(\frac{D_h}{l}\right) \quad (8)$$

where l is the distance in meters from the inlet to the considered section along the pipe. Instead of applying the constant pipe surface temperature, the equation taking into account the effect of the thermal entry region on the Nusselt number is used [18]:

$$\overline{Nu} = 3{,}66 + \frac{0{,}0688 \cdot Gz}{1 + 0{,}04 \cdot Gz^{\frac{2}{3}}} \quad (9)$$

where $\overline{Nu}$ is the average Nusselt number between the pipe inlet and the distance l along the pipe. Note that no correction is applied with respect to local changes of properties with temperature. The changes in dynamic viscosity may particularly affect the heat transfer rate and the ratio between viscosity at the bulk and viscosity at the pipe wall may be applied as a correction [19].

3. Results

Table 2, presents the experimental results of freezing point measurements for different ethyl alcohol base secondary fluids with denaturing agents. Note that the experimental results are compared with reference freezing point for EA20. Moreover, both ethyl alcohol samples containing ketones had higher total concentrations compared to samples with different alcohol based denaturing agents. As seen, the presence of two ketones as denaturing agents had a strong effect on the freezing point and a decrement in the freezing point was observed. EA20+MEK1.8+MIBK2.7 had the highest concentration of ketones and resulting in the lowest freezing point of -13.47 ºC. Meanwhile, propyl alcohol and n-butyl alcohol as denaturing agents had an opposite effect and an increment in the freezing point was observed. The highest freezing point of -10.45 ºC had been measured for EA17.5+PA2+BA0.5 having the highest content of propyl and n-butyl alcohols. This result can be explained by the fact that both propyl and n-butyl alcohol water based solutions have higher freezing points compared to EA20 [13]. Therefore, higher concentration of propyl and n-butyl alcohol in solution results in higher freezing point. Note that no reference data for the different ethyl alcohol solutions with denaturing agents were found and the freezing temperatures were compared to pure EA20 solution.

Table 2. Freezing point results.

Sample	$T_{f\ exp}$ (°C)	$T_{f\ ref}$ (°C)	Difference (K)
EA20	-10.92	-10.92	0.00
EA18+PA1.6+BA0.4	-10.58	-10.92	+0.34
EA17.5+PA2+BA0.5	-10.45	-10.92	+0.47
EA20+MEK1.8+MIBK2.7	-13.47	-10.92	-2.55
EA20+MEK2+MIBK0.5	-12.21	-10.92	-1.29
water	0.07	0	0.07

Figure 1, presents the results of density measurements at 20 °C for different ethyl alcohol based secondary fluids with denaturing agents. As seen, the experimental result at 20 ºC was slightly higher by up to 0.3 % than the reference value for EA20 found in [13], [20-21], which could be related to the testing method. Lower difference of around 0.14 % between the experimental and reference value was obtained for water. Both propyl alcohol and n-butyl alcohol have higher densities than ethyl alcohol. Therefore, any changes in the alcohol concentrations affect slightly the density results.

Moreover, the densities of both methyl ethyl ketone as well as methyl isobutyl ketone are lower that the pure ethyl alcohol [13]. Thus, both EA20+MEK2+MIBK0.5 and EA20+MEK1.8+MIBK2.7 samples had the lowest densities among all tested samples.

Figure 2, presents the results of dynamic viscosity measurements. The results obtained for water were higher by up to 3 % compared to reference values [22] and EA20 results were lower by up to 3 % compared to references found in [20-21]. As seen, the presence of the denaturing agents in small concentration can significantly decrease the dynamic viscosity values in full temperature range compared to EA20. EA18+PA1.6+BA0.4 and EA20+MEK2+MIBK0.5 had the lowest dynamic viscosity at temperature of -8 ºC by up to 8.4 % and 7 %, respectively. Moreover, EA17.5+PA2+BA0.5 had lower dynamic viscosity by up to 3.5 % than EA20. Only EA20+MEK1.8+MIBK2.7 had the dynamic viscosity higher by up to 2 % compared to EA20. Thus, the chemical character and concentration of different denaturing agents influences in different way the obtained properties. Similar observations were reported for different blends of ethyl alcohol with propyl alcohol as well as ethyl alcohol with methyl ethyl ketone [11-12]. Therefore, the concentration of both ketones and alcohols as denaturing agents should be the lowest in order to decrease the dynamic viscosity of ethyl alcohol based secondary fluid.

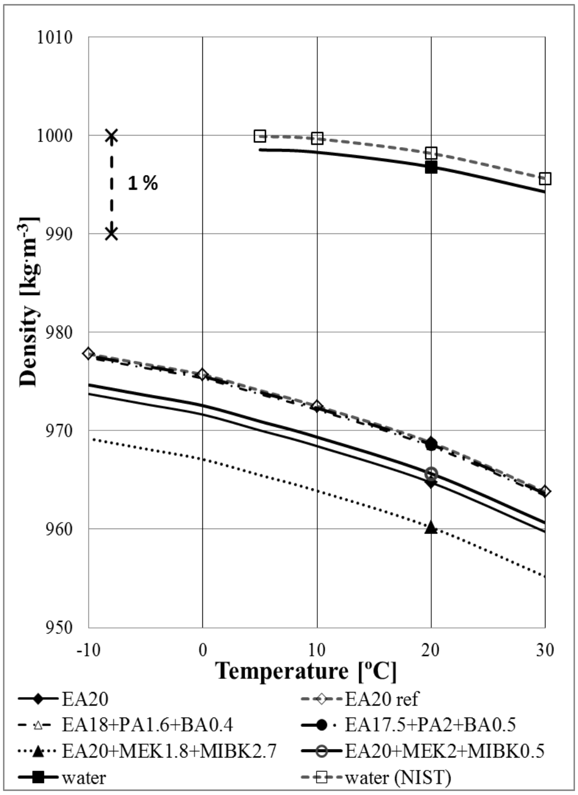

Fig. 1. Density results.

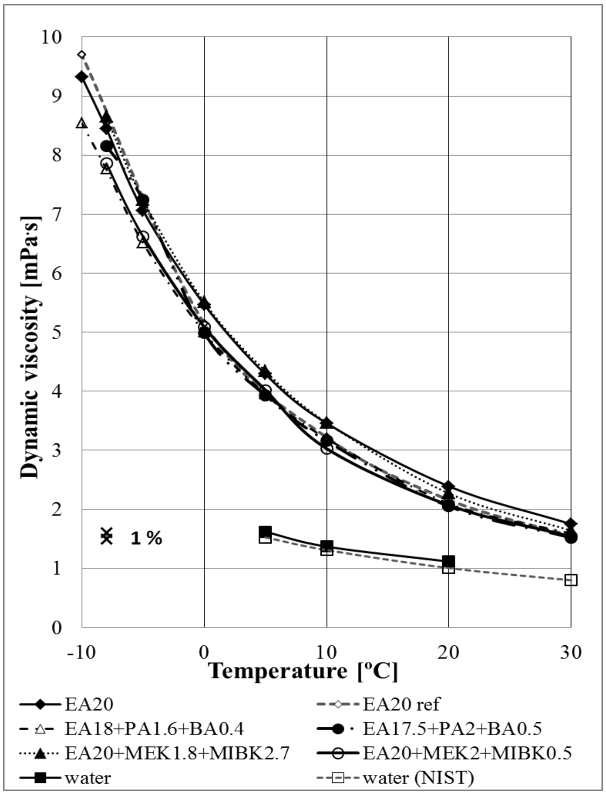

Fig. 2. Dynamic viscosity results.

Figure 3, presents the results of the thermal conductivity measurements. The difference between the experimental results and reference [22] for water was less than 0.7 % which is significantly below the measurement error of instrument set to be ± 2 % (~ 0.02 $W{\cdot}K^{-1}{\cdot}m^{-1}$). It is important to underline that the comparison of different alcohol blends is based on the experimental results obtained for EA20 in order to include in the analysis the measurement error. Note that the density and specific heat capacity are input values for post processing of thermal conductivity results since knowledge of the volumetric heat capacity, ρc_p, decreases the measurement error below 2 %. Due to the fact that sample volume is kept rather high (10 ml) the error of measurement was further decreased to 0.7 %. The standard deviation for 18 tests at one given temperature for each alcohol blend (10 different temperatures in total) gave a standard deviation between 0.0006 and 0.0036 $W \cdot m^{-1} \cdot K^{-1}$ and standard error of 0.00086 %. Higher values of specific heat capacity for EA20 could explain the steeper slope of curve compared to the reference data [21-22]. As seen, only EA18+PA1.6+BA0.4 had higher thermal conductivity by up to 2 % at temperature of -8 ºC than EA20. Moreover, EA17.5+PA2+BA0.5 had lower thermal conductivity values by up to 2.5 % at temperature of -8 ºC and 6 % at temperature of 5 ºC compared to EA20. The presence of denaturing agents in form of ketones had a negative effect on the thermal conductivity in full temperature range. EA20+MEK2+MIBK0.5 had the thermal conductivity values lower by up to 3 % at temperature of -8 ºC and 8 % at temperature of 5 ºC. Similar observation was made for EA20+MEK1.8+MIBK2.7 and values lower by up to 7 % at temperature of -8 ºC and 13 % at temperature of 5 ºC were observed. Previous results [23] showed that n-butyl alcohol present only at small concentrations can increase the thermal conductivity and propyl alcohol at same concentration is giving around 2 % higher value. This fact could explain the difference in slopes of EA17.5+PA2+BA0.5 and EA18+PA1.6+BA0.4 curves. Small changes in concentrations of three alcohols, especially ethyl and propyl alcohol, can affect the slope of obtained curve. Higher concentration of n-butyl alcohol makes the curve flatter at very low and high temperatures and its effect is becoming stronger at higher concentrations [23].

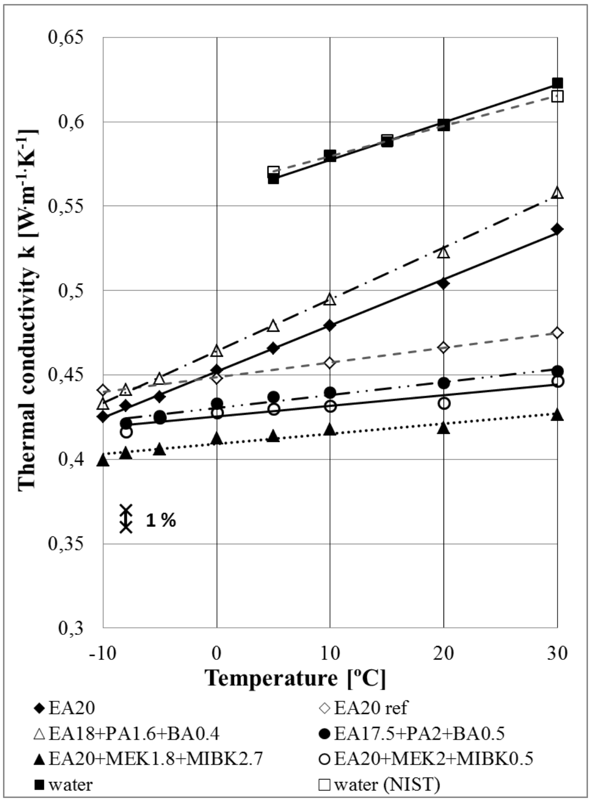

Fig. 3. Thermal conductivity results.

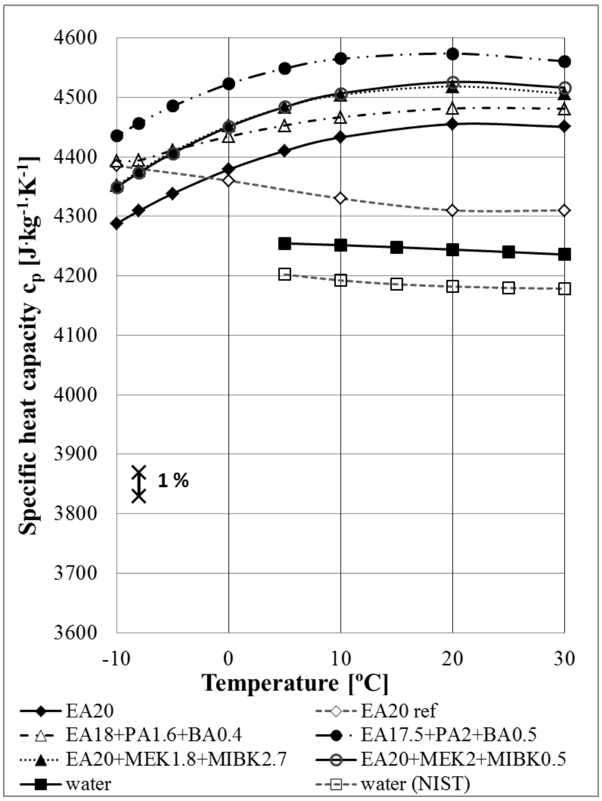

Fig. 4. Specific heat capacity results.

Figure 4, shows the results of the specific heat capacity measurements. The experimental results for water were up to 1.5 % higher whereas the accuracy of instrument is set to be ± 1 % (~ 10 $J \cdot kg^{-1} \cdot K^{-1}$) than references [22]. Higher measurement error obtained for the water could be explained by the small sample volume of 750 µl. The standard deviation for five tests for water was 24 $J \cdot kg^{-1} \cdot K^{-1}$. Thus, EA20 sample was used as the benchmark in this comparison. Recent results for EA20 solutions, showing a different tendency or slope than some literature values, were reported in [10-12]. EA17.5+PA2+BA0.5 had the highest specific heat capacity by up to 2.5 % than EA20 and by up to 1.5 % higher than EA18+PA1.6+BA0.4. EA20+MEK2+MIBK0.5 and EA20+MEK1.8+MIBK2.7 showed very similar results and gave by up to 1.5 % higher specific heat capacity compared to EA20. EA18+PA1.6+BA0.4 had higher specific heat capacity only in temperature range between -10 and -5 ºC (due to the small concentration of n-butyl alcohol) than both samples containing ketones. Similar results were reported in [10-11]. The results of density, dynamic viscosity, thermal conductivity and specific heat capacity for different ethyl alcohol based secondary fluids with denaturing agents are summarized in table 3 presented below.

Table 3. Thermophysical properties of different ethyl alcohol based secondary fluids with denaturing agents.

Sample	T (°C)	ρ ($kg \cdot m^{-3}$)	µ ($mPa \cdot s$)	k ($W \cdot m^{-1} \cdot K^{-1}$)	Cp ($J \cdot kg^{-1} \cdot K^{-1}$)
EA20	30	959.75	1.75	0.5362	4450.41
	20	964.75	2.39	0.5039	4454.96
	10	968.45	3.46	0.4793	4432.63
	5	970.05	4.29	0.4657	4409.85
	0	971.65	5.47	0.4525	4378.51
	-5	972.70	7.06	0.4369	4337.98
	-8	973.33	8.45	0.4319	4309.00
EA18+PA1.6+BA0.4	30	963.42	1.59	0.5581	4481.00
	20	968.42	2.10	0.5228	4481.40
	10	972.12	3.20	0.4950	4466.60
	5	973.72	3.95	0.4790	4452.75
	0	975.32	5.00	0.4642	4434.20
	-5	976.37	6.51	0.4479	4410.65
	-8	977.00	7.76	0.4413	4394.00
EA17.5+PA2+BA0.5	30	963.62	1.52	0.4522	4560.71
	20	968.62	2.05	0.4454	4573.60
	10	972.32	3.16	0.4395	4564.75
	5	973.92	3.93	0.4368	4548.50
	0	975.52	4.99	0.4329	4522.39
	-5	976.57	7.24	0.4256	4484.98
	-8	977.20	8.16	0.4214	4456.48

Sample (Cont.)	T (°C)	ρ (kg·m^{-3})	μ (mPa·s)	k (W·m^{-1}·K^{-1})	Cp (J·kg^{-1}·K^{-1})
EA20+MEK1.8+MIBK2.7	30	955.20	1.64	0.4267	4506.42
	20	960.20	2.27	0.4184	4525.78
	10	963.90	3.47	0.4178	4506.60
	5	965.50	4.34	0.4137	4483.68
	0	967.10	5.51	0.4127	4450.47
	-5	968.15	7.24	0.4060	4405.93
	-8	968.78	8.65	0.4038	4373.32
EA20+MEK2+MIBK0.5	30	960.66	1.54	0.4466	4516.44
	20	965.66	2.07	0.4332	4525.78
	10	969.36	3.03	0.4317	4506.60
	5	970.96	4.02	0.4299	4483.68
	0	972.56	5.09	0.4278	4450.47
	-5	973.61	6.62	0.4246	4405.93
	-8	974.24	7.86	0.4166	4373.32

Figure 5 and 6, present the convection heat transfer coefficients calculated using eq.(6) for two different pipe size and typically used flow rates (between 0.4 and 0.6 l·s^{-2}) found in BHEs taking into account experimentally obtained thermophysical properties. The performance of different ethyl alcohol based secondary fluids with different denaturing agents is investigated at the operational temperature of -5 °C. In all cases EA18+PA1.6+BA0.4 gives the highest convection heat transfer coefficient although EA20+MEK2+MIBK0.5 gives values only about 6 % lower. EA20+MEK1.8+MIBK2.7 gives the lowest convection heat transfer coefficient in all cases. In all cases EA20 is performing better than EA20+MEK1.8+MIBK2.7 and EA17.5+PA2+BA0.5. As seen, the convection heat transfer coefficients are lower for PE50 pipes than for PE40 pipes for the same flow rates due to lower average velocities of the secondary fluid. This may also lead to the establishment of the laminar flow regime in pipes which from the heat transfer perspective should be avoided. Moreover, the heat transfer area is larger in PE50 pipes than in PE40 pipes and it should be taken into account by comparing fluid-to-pipe thermal resistance instead of the heat transfer convection coefficient. Additionally, lower velocities imply also lower pressure drops. The pressure drop along a 250 PE40 U-pipe, i.e. with a total length of 500 m for the flow rate of 0.6 l·s^{-1} would be about: 234 kPa (EA18+PA1.6+BA0.4); 235 kPa (EA20+MEK2+MIBK0.5); 239 kPa (EA20); 240 kPa (EA20+MEK1.8+MIBK2.7) and 242 kPa (EA18+PA2+BA0.5). In the configuration with a PE50 U-pipe, the pressure drops for the flow rate of 0.6 l·s^{-1} would be: 80 kPa (EA18+PA1.6+BA0.4); 81 kPa (EA20+MEK2+MIBK0.5); 83 kPa (EA20); 83.5 kPa (EA20+MEK1.8+MIBK2.7) and 84 kPa (EA18+PA2+BA0.5). Note that only friction losses are accounted in these estimations. The trends for the convection heat transfer coefficients and head losses were the same for temperatures of 5 °C and 0 °C.

Thus, the product commonly used in Sweden (EA18+PA1.6+BA0.4) presents the best characteristics in terms of higher heat transfer (up to 10 %) and lower pressure drop (up to 2.7 %) among different commercial products. EA20+MEK2+MIBK0.5 used in Switzerland showed second best performance in terms of higher heat transfer (up to 5 %) and lower pressure drop (up to 2 %). Moreover, EA17.5+PA2+BA0.5 and EA20+MEK1.8+MIBK2.7 present the worst performance both in terms of lower heat transfer and higher pressure drop. EA20+MEK1.8+MIBK2.7 gave by up to 8 % lower heat transfer and by up to 0.5 % higher pressure drop. EA17.5+PA2+BA0.5 gave by up to 3 % lower heat transfer and by up to 1 % higher pressure drop than EA20.

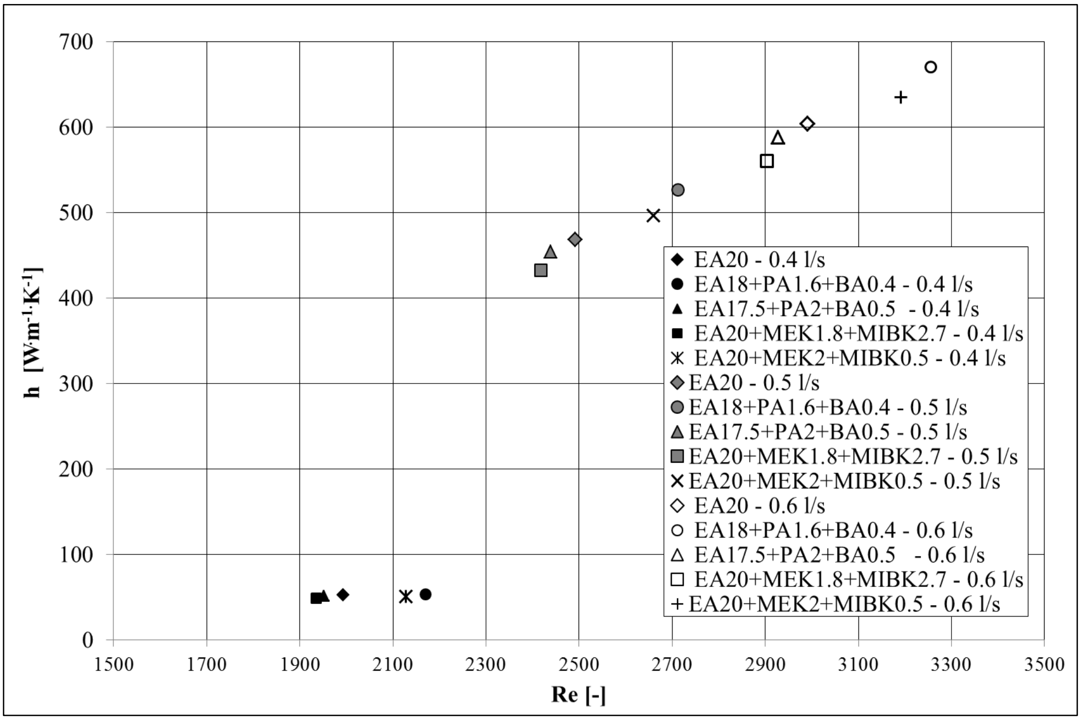

Fig. 5. Convection heat transfer coefficient vs Re number for different flow rates in PE40 x 2.4 mm U-pipe BHE at T = -5 °C.

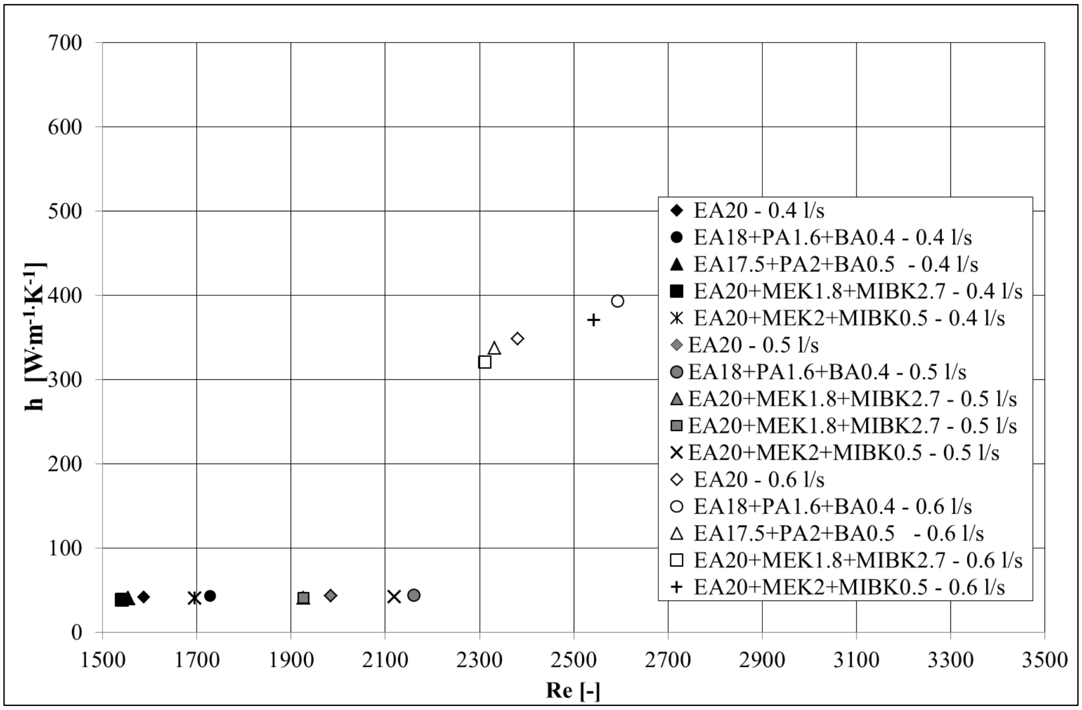

Fig. 6. Convection heat transfer coefficient vs Re number for different flow rates in PE50 x 2.9 mm U-pipe BHE at T = -5 °C.

4. Conclusions

This study showed that the chemical character of various denaturing agents and concentrations can in a different way affect the thermophysical properties. As seen, EA20+MEK2+MIBK0.5 and EA20+MEK1.8+MIBK2.7 had the lowest freezing point among all samples. Both propyl and n-butyl alcohols increased density while methyl ethyl and methyl isobutyl ketones were giving lower density values compared to pure EA20. The small concentration of denaturing agents seems to decrease the dynamic viscosity values in full temperature range. EA18+PA1.6+BA0.4 and EA20+MEK2+MIBK0.5 had the lowest dynamic viscosity at temperature of -8 ºC by up to 8.4 % and 7 %, respectively. Only EA20+MEK1.8+MIBK2.7 had the dynamic viscosity higher by up to 2 % than EA20. As seen, the presence of ketones had a negative effect on the thermal conductivity in full temperature range. Only EA18+PA1.6+BA0.4 showed higher thermal conductivity by up to 2 % compared to EA20. EA17.5+PA2+BA0.5 had the highest specific heat capacity, higher by up to 2.5 % compared to EA20 and by up to 1.5 % higher than EA18+PA1.6+BA0.4. EA20+MEK2+MIBK0.5 and EA20+MEK1.8+MIBK2.7 showed very similar results and gave by up to 1.5 % higher specific heat capacity compared to EA20.

Summing up, the commercial product commonly used in Sweden (EA18 + PA1.6 + BA0.4) presented the best characteristics in terms of the higher heat transfer (up to 10 %) and lower pressure drop (up to 2.7 %) among different products found in Europe. EA20+MEK2+MIBK0.5 used in Switzerland showed second best performance in terms of both higher heat transfer (up to 5 %) and lower pressure drop (up to 2 %). Moreover, EA17.5+PA2+BA0.5 and EA20+MEK1.8+MIBK2.7 presented the worst performance both in terms of the heat transfer and pressure drop. EA20+MEK1.8+MIBK2.7 gave lower heat transfer by up to 8 % and higher pressure drop by up to 0.5 %. EA17.5+PA2+BA0.5 gave lower heat transfer by up to 3 % and higher pressure drop by up to 1 % than EA20.

Nomenclature

BA	n-butyl alcohol
BHE	Borehole Heat Exchanger
c_p	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D_h	hydraulic diameter (m)
ε	relative roughness (m)
EA	ethyl alcohol
exp	experimental
f	friction factor (-)
g	gravitational acceleration ($m \cdot s^{-2}$)
GSHP	Ground Source Heat Pump
Gz	Graetz number (-)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
L	total pipe length (m)
l	distance (m)
MEK	methyl ethyl ketone
MIBK	methyl isobutyl ketone
Nu	Nusselt number (-)
Δp	pressure drop (kPa)
PA	propyl alcohol
PE	Polyethylene
Pr	Prandtl number (-)
PN	nominal pressure (bar)
Re	Reynolds number (-)
ref	reference
T	temperature (ºC)
u	fluid mean velocity ($m \cdot s^{-1}$)
vol-%	volume concentration (-)
wt-%	weight concentration (-)
μ	dynamic viscosity ($mPa \cdot s$)
ρ	density ($kg \cdot m^{-3}$)

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