Effect of additives in a working medium on its heat transfer performance

Group 138

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Abstract

Bluerise has developed a system that uses cold seawater to cool down a fresh water loop. This loop is used for fresh water production. The goal of this study is to improve the overall heat transfer coefficient of the working medium in this system by at least 5%, which will also reduce its size. The overall heat transfer can be improved by adding various additives to the water, although this new medium also requires more power to pump it through the system. The examined additives are: immiscible- and miscible fluids, and nanoparticles. After a theoretical analysis it became clear that only the nanoparticles improve the heat transfer. Experiments showed that a 0.5 and 1 %vol Al_2O_3 nanoparticles suspended in water gives respectively an enhancement of the heat transfer coefficient of between 0.8% and 22.3% compared to water, not taken into account agglomeration or pollution of the system. However, with a higher pressure-drop, the ratio of pump power needed per heat transfer deteriorated by a maximum of 80%, so although the initial goal of a 5% improvement of heat transfer coefficient is achieved, additional impacts need to be taken into account.

Keywords: Nanoparticles, Heat transfer, Fresh water, Additives, Heat exchanger, Bluerise, Pressure drop

1. Introduction

This research is conducted as part of the design process for a fresh water production system in tropical areas using direct contact condensation being designed by the company Bluerise (Bluerise, 2014). In this system a heat exchanger, which cools down a fresh water loop, shown schematically in Figure 1, plays a significant role. This cooled water is used to saturate a stream of hot air, from which more water is condensed while travelling through a packed-bed column, yielding fresh water for several uses, (Lie et al., 2014).

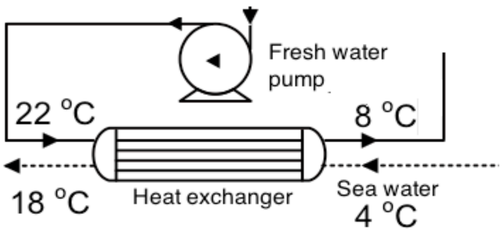

Figure 1 - Heat exchanger for cooling freshwater loop

The size of the heat exchanger depends mostly on the heat transfer between the two media. To downsize the heat exchanger, which is financially interesting, would mean that heat transfer between the two flows needs to be improved while keeping pump power low. The effect of additives to the working medium and its impact on heat transfer within the heat exchanger will be studied. It is expected that using additives in the working medium will result in an increase in heat transfer coefficient between the media of at least 5%, seeing that the additives have better thermodynamic properties.

2. Method

Miscible fluids, immiscible fluids and nanoparticles were considered to be three additives that could be used to achieve a better convective heat transfer. Viscosity, specific heat, density, and thermal conductivity change due to additives in a suspension, emulsion or mixture. Solving equation (1) with new physical properties allows for the calculation of the improvement in heat transfer ratio ${}^{h_m}/{}_{h_w}$ for turbulent flow of the medium, where m and w denote mixture and pure water, respectively.

$$\frac{h_m}{h_w} = \left(\frac{\rho_m}{\rho_w}\right)^{0.8} * \left(\frac{\kappa_m}{\kappa_w}\right)^{0.7} * \left(\frac{C_{p_m}}{C_{p_w}}\right)^{0.3} * \left(\frac{\mu_w}{\mu_m}\right)^{0.5} \tag{1}$$

This formula has been obtained by expanding the equations for the heat transfer coefficient, the Reynolds number and the Prandtl number. With this ratio the new medium can easily be judged on performance as a working fluid. Although density positively contributes to a higher heat transfer coefficient, the next step is to calculate pressure drop using the new physical properties and determine the new pump power needed per unit heat transfer to ensure that the net work is lowered. This is done by solving equations (2) and (3) for the new physical properties. And comparing the Power quotient: P_{pump}/Q.

$$P_{pump} = \left(\frac{\dot{m}}{\rho}\right)\Delta P \tag{2}$$

$$Q = U * \pi * d * L * \Delta T \tag{3}$$

3. Additives and theoretical work

At first immiscible fluids were thought to be suitable additives for this process. However, during exploratory research, immiscible and miscible fluids were found to deteriorate the heat transfer. For example, a volume fraction of 1% octanol deteriorated the heat transfer coefficient by more than 3.1% and a volume fraction of 1% ethylene glycol deteriorated the heat transfer coefficient by 5.3%. Only nanoparticles were found to have a positive effect on the heat transfer coefficient. Table 1 shows the theoretical improvement of the heat transfer coefficient with the use of a volume fraction of 1% of several nanoparticles in a turbulent flow.

Table 1 – Theoretical improvement using nanoparticles

Particle	H_2O (ref)	Al_2O_3	Fe	Mg
ρ[kg/m³]	998	1028	1067	1006
C_p[J/kg.K]	4182	4054	3906	4127
Rise h_m/h_w %	--	20.3	22.5	18.8

Table 2 shows the theoretical power quotients of several suspensions of Al_2O_3 nanoparticles in water at a Reynolds number of $4.6*10^4$.

Table 2 – Power quotient for several fractions of nanoparticle suspensions

Fraction	0.0 %vol	0.5%vol	1.0%vol
Power Quotient	0.273	0.307	0.401

The rise of power quotient means that the efficiency of the heat exchanger will deteriorate when nanoparticles are added to the working medium.

4. Experimentation

To verify theoretical calculations an experimental setup in the Process and Energy lab is used. This is initially meant for a CO_2 hydrate slurry, but is also extremely convenient for testing several other working media. In this case, three suspensions of aluminum oxide (Al_2O_3) nanoparticles in water are tested, 0.0, 0.5 and 1.0 %vol respectively. The first suspension tested (0.0%vol) is set as the reference reading for the original system. The three suspensions are tested at four different Reynolds numbers, also to determine the relation between flow velocity, density and heat transfer coefficient. The setup uses two thermostatic baths to heat and cool the working medium. The schematic of this system is shown in Figure 2.

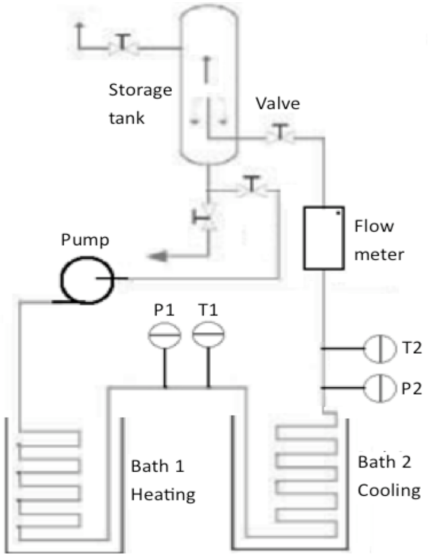

Figure 2 - Experimental Setup for CO_2 hydrate slurry

The inlet and outlet temperatures of bath 2, T1 and T2 resp., are then used to calculate the heat transfer coefficient using equations (4) and (5):

$$\dot{q} = \frac{\dot{m} C_p (T_2 - T_1)}{\pi d_h l} \tag{4}$$

$$h = \frac{\dot{q}}{(T_{wall} - T_{bulk})} \tag{5}$$

Where T_{wall} is the temperature of the tube wall throughout the process and T_{bulk} is the average temperature of the working medium. After this, the comparison is made between the theoretical calculations and the experimental outcomes to determine the validity of the model used. These experimental outcomes are also used as definitive results for the research.

5. Results

After experimentation, further calculations were made to determine if the initial goal of a 5% rise of the heat transfer coefficient is achieved, and what the increase is of the power quotient. The results of these calculations are shown in Tables 3 and 4, and including reference readings in Figure 3.

Table 3 – Percentage increase in heat transfer coefficient

Reynolds number	967	2841	4674	6466
0.5 %vol	17.3 %	9.5%	0.8%	3.4%
1.0 %vol	13.8%	20.4%	9.8%	22.3%

Table 4 – Rise in Power Quotient of the heat transfer

Reynolds number	967	2841	4674	6466
0.5 %vol	3.3%	15.6%	13.3%	12.0%
1.0 %vol	29.3%	63.8%	73.3%	80.0%

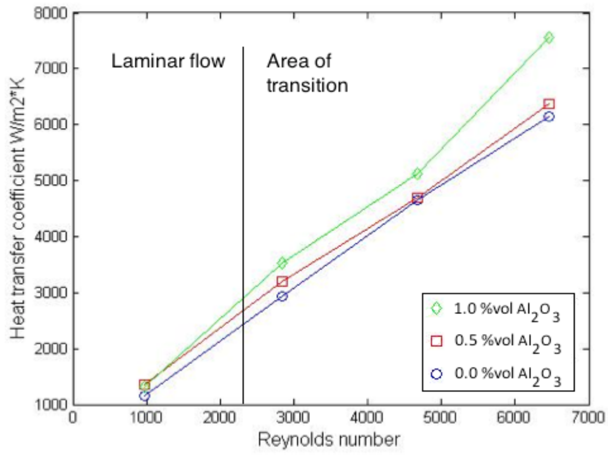

Figure 3 - h [W/m^2*K] at specific Reynolds number

6. Discussion

Although the results for the heat transfer coefficient were positive, further calculations have proven that the use of nanoparticles in a water flow is not beneficial for the power consumption. Perhaps initial costs can be avoided when using nanoparticles because a smaller heat exchanger is necessary, but running costs can build up quickly. Also during experiments, agglomeration of nanoparticles and settling of the suspension may have influenced the accuracy of the measurements. Taking this into account, the improvement of 22.3% is still well above the initial goal of 5%.

Then comes the part of the separability of the nanoparticles from the suspension. Nanofiltration is an extremely time and power consuming process, so the use of nanoparticles in this system is devaluated even more.

7. Conclusion

With a maximum improvement of 22.3% for a 1.0 %vol mixture, adding nanoparticles to a working medium proves to be even more beneficial than expected. The initial goal of a minimal improvement of 5% of the heat transfer coefficient is achieved.

Nomenclature

Symbols

C_p	*Specific heat*	$[KJ/kg\ K]$
d	*Diameter*	$[m]$
h	*Heat transfer coefficient*	$[W/m^2K]$
κ	*Thermal conductivity*	$[W/m\ K]$
l	*Tube length*	$[m]$
$\dot{m}$	*Mass flow*	$[kg/s]$
μ	*Dynamic viscosity*	$[Pa\ s]$
$\dot{q}$	*Heat flux*	$[W/m^2]$
Q	*Total heat transfer*	$[W/m^2]$
ρ	*Density*	$[kg/m^3]$
ΔP	*Pressure drop*	$[kPa]$
P_{pump}	*Pump power*	$[kW]$
T	*Temperature*	$[°C]$
U	*Local heat transfer*	$[W/m^2K]$

Subscripts

m	*mixture of water and nanoparticles*
w	*water*
$wall$	*inner tube wall*
$bulk$	*bulk of working medium*
h	*Hydraulic*

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