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RESEARCH ARTICLE

Influence of Nanofluid on the Performance of Crystallization

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Abstract: Nanofluids, the fluid suspensions of nanomaterials , have shown many interesting properties, and the distinctive feature offer unprecedented potential for many applications. Nanofluids which are known as new generation of thermal fluids have particular feature which are affected on their behavior. Present paper focuses on behavior of nanofluids in crystallization. The objectives of this paper are to visualize the effect of nanofluid in crystallization operation as compared to convectional fluids *i.e* water (DW). Results are presented in terms of heat transfer coefficient. For 1% nanofluid heat transfer coefficient is 255.645 w/m^{2o}K and 264.438 w/m^{2o}K for 3% nanofluids which enhance significantly the crystallization performance. The use of CuO nanofluids in crystallizer increases the yield of crystallizer. The percentage increase in yield for 1% nanofluids is 4.4% and for 3% nanofluids percentage increase in yield was 5.5%. The nanoparticles used in the experiment was 98.5% pure copper oxide, with an average particle size of 32 nm synthesized by using chemical precipitation method. The nanofluid was prepared by mixing nanoparticles with de-ionized water to prepare experimental concentration of 1% and 3%. The magnesium sulfate solution to be crystallizing is prepared in lab and the average percentage increases heat transfer coefficients for 1% nano-Fluid was found to be 13.1% and 22.31 for 3% nanofluids.

Keywords: Nanofluids, Nanoparticles, Heat transfer, Heat transfer coefficient, Yield

Introduction

In much industrial application, fluids are generally used as a cooling medium and enhancement of the heat transfer behavior of those fluids is of great importance in many applications[1]. Nanofluids are dilute liquid suspensions of nanoparticles with at least one of their principal dimensions smaller than 100 nm. The size of nanoparticles in liquid mixture gives them the ability to interact with liquids at molecular level and so, conduct heat better than today's heat transfer fluids[2]. From previous investigation, nanofluids have been found to posses enhanced heat transfer coefficient in heat exchanger as compared to base fluids. In the present paper, nanofluids was applied in a crystallization unit operation and the study of heat transfer coefficient which will higher than convectional fluids. Crystallization is a separation process where solid particles form within a homogenous liquid phase due to super saturation induced through cooling so in this study we are focusing on the study of heat transfer.

The previous studies that are related with[3] forced convection flow of water - aluminum oxide (Al_2O_3) and ethylene glycol nanofluids inside a uniformly heated tube subjected to constant and uniform heat flux at the wall. The study concluded that the use of nanoparticles increased the heat transfer at the tube wall considerably for both laminar and turbulent flow. Experimentally studied the convective heat transfer of nanofluids flowing through a copper tube in the laminar flow regime. The results showed that there is considerable enhancement of convective heat transfer using the nanofluids. The study also found that the classical Shah equation failed to predict the heat transfer behavior of nanofluids[4]. The study used copper particles in water as the nanofluid and measured the convective heat transfer coefficient and friction factor of the nanofluid for turbulent flow and proposed a convective heat transfer correlation for the nanofluid heat transfer[5].

Experimental

Preparation of nanofluids is the first key step in experimental studies with nanofluids. The nano-particle of an average particle size of 32 nm was made by using chemical precipitation method[6]. The nanofluid was prepared by mixing with de-ionized water to prepare experimental concentrations. The mixture of nanoparticles in deionised water was vigorously stirred at the about 4000 rpm for 4 hours for uniform distribution of nanoparticles in the base fluid (de-ionised water)[7]. The nanofluids with less than 4% nanoparticles concentration were found to be stable and the stability lasted over a week, no intermediate mixing was considered necessary. 1% Concentration of nanofluid was prepared by mixing 100 g of 98.5% of copper oxide 10 L. deionised water (*i.e* 1 g of CuO nanoparticle in 100 mL of deionised water) under vigorous stirring of about 4000 rpm[8] For preparing 3% concentration of nanofluid, when we added 200 g 0f copper oxide powder in 1% concentrated solution to convert it into 3% we observed that even after the vigorous stirring of solution at about 4000 rpm, the particles of copper oxide started settling in the bottom of the tank[9]. This is due to the reason explained above as the concentration is below 4% , the solution was not stable after 6 or 7 days and copper oxide particles in it started settling after six days or one week[6]. When we were using that solution to test the performance crystallizer just after its vigorous stirring at very high values of rpm, the nanoparticles in the solution started settling within a fraction of minute[7]. The performance of crystallizer with this type of solution was resembling to that with the base fluid (deionised water). So for preparing 3% of concentration of nanoparticles we further took the fresh 10 L of deionised water and mixed 300 g of copper oxide nanoparticles in it. Then we used the solution to test the performance crystallizer. The solution stability was over a week long[10].

Preparation of magnesium sulfate solution

The magnesium sulfate used in this experiment was supplied by thermo fisher scientific India company, (India) through chemical corporation, Nagpur (India). Magnesium sulfate crystals are in heptahydrate form ($MgSO_4.7H_2O$). We prepared 25% concentrated solution of magnesium sulfate by adding 25 g of ($MgSO_4.7H_2O$) in 100 mL of distilled water with continue stirring.

The distilled water was initially heated to 90 ^oC. Then magnesium sulfate crystals were added to it until traces of crystals were left to dissolved in it. For preparing 25% solution of magnesium sulfate in 1200 mL of water 400 g of ($MgSO_4.7H_2O$) required. Thus after complete stirring the magnesium sulfate solution is obtained[11].

Crystallizer

Type - batch crystallizer, material - stainless steel (k = 16.5 W/mK), dimensions - D1 = 14.20 cm, D2 = 14.00 cm, D3 = 16.20 cm, D4 = 16.50 cm

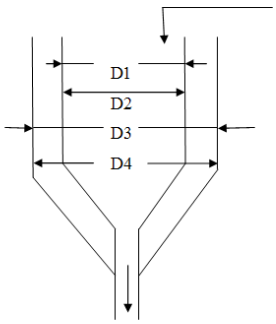

Figure 1. Schematic representation of crystallizer

Fluid in the inner cylinder

$MgSO_4$ solution, fluid in the outer jacket:-cold water, Nano-fluid

Hot fluid cylinder

- It is cylindrical in shape with conical bottom having capacity of 5 L.
- It is provided with a stirrer, to achive uniform temperature.
- Heating coil is provided inside the tank.
- A thermocouple and a control system are provided to maintain a constant temperature.
- And 1 valve is provided at the extreme bottom for discharge of mother liquor.

Cold water tank

- It is rectangular in shape having capacity of 15 L.
- It is provided with a submersible pump to pump the liquid through the jacket.
- It contains cold water at 18 ^oC.

Nanofluid tank

- It is rectangular in shape having capacity of 15 L.
- It is provided with a submersible pump to pump the liquid through the jacket.
- It contains cold water at 18 ^oC.

Jacket of cylinder

- It is cylindrical in shape with conical bottom.
- It consist of 3 valves, one for inlet of cold fluid at the bottom, one for outlet of cold fluid and one for discharge of remaining fluid.

Pump

- It is centrifugal type submersible pump.
- Maximum pumping flow rate through the jacket was found to be 100 L/h.

Thermocouples

- T1 thermocouple was placed at mouth of cylinder of hot solution.
- T2 thermocouple was placed at inlet of cold fluid.
- T3 thermocouple was placed at outlet of cold fluid.

In this experiment, the crystallizer made up of stainless steel and jacketed from outside. The inside and outside diameter of inner tank is 14 cm and 14.2 cm respectively. And the inside diameter of jacket is 16.2 cm and outside diameter is 16.5 cm. The length of crystallizer tank is 25 cm. Before starting the performance, the prepared magnesium sulfate solution was kept at a constant and maintained initial temperature at 60 ˚C with the help of heating tank in crystallizer consisting heater and stirrer in which the constant temperature is maintained by control system consisting of thermocouple[12]. The magnesium sulfate solution was kept in inner tank of crystallizer and the cold fluid flows through annular space between inner tank and jacket. Agitator is provided in inner tank for continue agitation of solution and the angular speed of agitator is controlled and maintained by control system[13]. The nanofluid is always used as a coolant. The pump is used to flow the cold fluid through the jacket whose flow rate is controlled by the valve at the inlet nozzle of jacket and flow rate is measured by rotameter provided in crystallizer. The pump is provided with bypass to avoid the back pressure of the cold fluid[14].

Experimental procedure

As the comparison is between the performance of crystallizer with nanofluid (1% CuO/ water) and the base fluid (water). First the performance of crystallizer with base fluid (water) then with nanofluids were checked. The initial temperature of inlet of hot solution and cold fluid were constant but later inlet and outlet temperature of hot solution and cold fluid varies throughout the experiment and the flow rate of hot fluid was also constant. The study of variation in performance of crystallizer with different flow rate of cold fluid (nanofluid and base fluid) and volumetric concentration of nanofluid was done. While doing this the inlet temperature of hot solution in the heating tank was maintained at 60 ^{o}C and the inlet temperature of cold fluid was maintained at 18 ^{o}C. As the cold fluid was recycled trough same tank its inlet and outlet temperature varies gradually[10]. The inlet temperature of cold fluid goes on increasing while outlet temperature goes on deceasing. The hot solution inside the tank was agitated slowly at 1.3 rps. The flow rate of cold fluid was set[5].

First of all hot solution of magnesium sulfate was introduced in the inner tank and heater was started to attained the temperature of 60 ^{o}C with constant agitation for few minutes, so that the wall of inner tank attains the constant temperature of hot solution[3]. Then the pump was started to flow the cold fluid through the jacket. As soon as cold fluid starts flowing the hot fluid starts cooling with high rate and temperature of all the three *i.e.* inlet temperature of cold fluid, outlet temperature of cold fluid, temperature of solution were measured by temperature indicator of control system[2]. The temperatures of both the hot and cold fluids were notes down. After efficient cooling of hot solution of magnesium sulfate for several hours the crystals of magnesium sulfate starts forming and when the temperature of hot solution of magnesium sulfate is reached to its minimum value the crystals formed[7]. The mother liquor was discharged from the outlet provided at the bottom of tank. The supernatant solution of mother liquor was discarded carefully. The crystals of magnesium sulfate were filtered and then it was heated in oven at 50 ^{o}C. The anhydrous powder of magnesium sulfate was obtained. Repeat the procedure for different flow rates and compare the yield of anhydrous magnesium sulfate obtained[15].

For studying the performance of crystallizer using nanofluid as a coolant, the same above procedure and same inlet temperature of hot and cold fluids was repeated just by replacing the base fluid (water) by nanofluid, and the readings of temperature of hot solution and inlet and outlet temperature of nanofluid were noted down for seven different flow rates[8]. Now the second part of the experiment was to study the performance of the crystallizer at increased concentration of nanofluid (3% volumetric concentration). For which 300 g of CuO was mixed in 10 L of distilled water under vigorous stirring at 4000 rpm[1]. In this case also the same procedure was repeated which was done for 1% volumetric concentration.

Observation table

The effect of flow rate on the performance of crystallization is given in Table 1 to Table 3.

Table 1. Effect of cold fluid flow rate on crystallizer

S. No.	Cold fluid flow rate, l/h	Cold fluid flow rate Kg/sec	$T_{solution\ in}$	$T_{solution\ out}$	$T_{cold\ in}$	$T_{cold\ out}$
1.	80	0.0222	60	21 .5	18	55.9
2.	70	0.0194	60	21.1	18	56.2
3.	60	0.0167	60	20.6	18	56.8
4.	50	0.0138	60	20.0	18	57.3
5.	40	0.0111	60	19.5	18	57.9
6.	30	0.0083	60	19.1	18	58.4
7.	20	0.005	60	18.8	18	59.1

Table 2. Effect of 1% nanofluid flow rate on crystallizer

S. No.	Cold fluid flow rate, l/h	Cold fluid flow rate, Kg/sec	$T_{solution\ in}$	$T_{solution}$	$T_{cold\ in}$	$T_{cold\ out}$
1.	80	0.0222	60	21.2	18	56.1
2.	70	0.0194	60	20.9	18	56.6
3.	60	0.0167	60	20.1	18	57.3
4.	50	0.0138	60	19.7	18	57.8
5.	40	0.0111	60	19.1	18	58.3
6.	30	0.0083	60	18.8	18	58.8
7.	20	0.005	60	18.4	18	59.4

Table 3. Effect of 3% nanofluid flow rate on crystallizer

S. No.	Cold fluid flow rate, l/h	Cold fluid flow rate, Kg/sec	$T_{solution\ in}$	$T_{solution}$	$T_{cold\ in}$	$T_{cold\ out}$
1.	80	0.0222	60	20.9	18	56.4
2.	70	0.0194	60	20.5	18	57.0
3.	60	0.0167	60	19.9	18	57.5
4.	50	0.0138	60	19.3	18	58.1
5.	40	0.0111	60	19.0	18	58.6
6.	30	0.0083	60	18.6	18	59.1
7.	20	0.005	60	18.1	18	59.6

The relationship between time and temperature for cold fluid with flow rate 20 l/h and magnesium sulfate solution is given in the Table 4 to Table 6.

Table 4. Variation of water and $MgSO_4$ solution with respect to time

Time, min	Temperature of water, ˚C	Temperature of $MgSO_4$ solution, ˚C
0	18	60
40	29.2	49.1
80	38.8	41.6
120	46.6	34.9
160	51.5	27.3
200	55.2	22.6
240	59.1	18.8

Table 5. Variation of 1 % nanofluid and $MgSO_4$ solution with respect to time

Time min	Temperature of 1% nanofluid, ˚C	Temperature of $MgSO_4$ solution, ˚C
0	18	60
40	30.1	47.9
80	39.9	40.3
120	47.8	33.8
160	52.3	26.1
200	56.5	21.8
240	59.4	18.4

Table 6. Variation of 3 % nanofluid and $MgSO_4$ solution with respect to time

Time, min	Temperature of 3% nanofluid, ˚C	Temperature of $MgSO_4$ solution, ˚C
0	18	60
40	31.4	46.8
80	41.5	39.4
120	49.2	32.5
160	53.6	24.9
200	57.1	21.1
240	59.6	18.1

The density, specific heat, viscosity and thermal conductivity of nanofluids was calculated based on following equations[16].

$$\rho_{\text{nanofluid}} = (1-\varphi)\,\rho_{\text{base fluid}} + \varphi\,\rho_{\text{particle}} \tag{1}$$

$$(C_p)_{\text{nanofluid}} = (1-\varphi)\,(C_p)_{\text{base fluid}} + \varphi\,(C_p) \tag{2}$$

$$\mu_{\text{nanofluid}} = \mu_{\text{base fluid}}\,(1+ 39.11\,\varphi + 533.9\,\varphi^2) \tag{3}$$

$$k_{\text{nanofluid}} = k_{\text{base fluid}}\,(1+ 7.47\,\varphi) \tag{4}$$

The thermal properties of nanofluids is given in Table 7.

Table 7. Properties of nanofluids

Vol. fraction (φ) (%)	Density (ρ) (kg / m³)	Specific heat (Cp) (J/kgK)	Viscosity (μ) (N-s/m²)	Thermal conductivity (k) (W/m°K)
0.5	1011.575	4166.452	0.001077	0.62241
1	1038.150	4145.908	0.001287	0.64482
2	1091.300	4104.816	0.001778	0.68964
3	1144.450	4063.752	0.002365	0.73446
4	1197.600	4022.633	0.003046	0.77928
5	1250.750	3981.542	0.003823	0.8241

Outside heat transfer coefficient

The heat transfer coefficient obtained from the calculation is given in the Table 8 to 10.

Table 8. Heat transfer coefficient (ho and U_o) for water in crystallizer

Re	Pr	Nu	h_o W/m²K	U_o W/m²K
1586.19	6.21796	16.638	512.84	241.00
1386.13	6.21796	16.343	490.29	236.79
1193.215	6.21796	15.547	466.41	231.10
986.01	6.21796	14.59	437.70	223.81
793.095	6.21796	13.568	400.74	213.72
593.035	6.21796	12.315	369.45	204.50
357.25	6.21796	10.4	312.00	185.52

Table 9. Heat transfer coefficient (ho and U_o) for 1 % nanofluid in crystallizer

Re	Pr	Nu	h_o W/m²K	U_o W/m²K
1104.137	8.2750	17.951	578.748	255.645
964.876	8.2750	17.162	553.32	250.557
830.589	8.2750	16.326	526.36	244.877
686.355	8.2750	15.320	493.932	237.62
552.068	8.2750	14.248	459.369	229.32
412.808	8.2750	12.932	416.94	218.233
248.679	8.2750	10.922	352.136	199.058

Table 10. Heat transfer coefficient (ho and U_o) for 3 % nanofluid in crystallizer

Re	Pr	Nu	h_o W/m²K	U_o W/m²K
579.84	13.079	17.043	625.87	264.438
522.437	13.079	16.294	598.364	259.4
449.727	13.079	15.500	569.206	253.764
371.63	13.079	14.545	534.136	246.547
298.92	13.079	13.527	496.752	238.27
223.517	13.079	12.278	450.884	227.185
134.65	13.079	10.37	380.817	207.91

Percentage increase in jacket side heat transfer coefficient is given in Table 11 to Table 13.

Table 11. Percentage increase in jacket side heat transfer coefficient

h_o for water	h_o for 1% N.F.	h_o for 3% N.F.	% increase in 1% N.F.	% increase in 3% N.F.
512.84	578.748	625.87	12.85	22.04
490.29	553.32	598.364	12.85	22.04
466.41	526.36	569.206	12.85	22.04
437.70	493.932	534.136	12.84	22.03
400.74	459.369	496.752	14.63	23.95
369.45	416.94	450.884	12.85	22.04
312.00	352.136	380.817	12.86	22.05

The average percentage increase in jacket side heat transfer coefficients for 1% Nano-Fluid was found to be 13.1%. And, for 3% Nano-Fluid the average percentage increase was 22.31%.

Table 12. Percentage increase in overall heat transfer coefficient

h_o for water	h_o for 1% N.F	h_o for 3% N.F.	% increase in 1% N.F.	% increase in 3% N.F.
241.00	255.645	264.438	6.07	9.72
236.79	250.557	259.4	5.81	9.54
231.10	244.877	253.764	5.96	9.75
223.81	237.62	246.547	6.17	10.15
213.72	229.32	238.27	7.29	11.48
204.50	218.233	227.185	6.71	11.09
185.52	199.058	207.91	7.29	12.06

The average percentage increase in jacket side heat transfer coefficients for 1% nano-fluid was found to be 6.47%. And for 3% nano-fluid the average percentage increase was 10.54%.

Table 13. Percentage increase in yield of anhydrous $MgSO_4$

Fluid	%Water evaporated	Theoretical yield, g	Actual yield, g	% increase in yield
Water	3	430	429.1	
1% Nanofluid	3.4	436.52	432.12	4.4
3% Nanofluid	4.5	440.14	434.81	5.33

Results and Discussion

From the Figure 2 it can be said that as the flow rate of cold fluid increases, individual heat transfer coefficient for outer surface of tube increases. Here also increase in heat transfer coefficient is more in case of nanofluid.

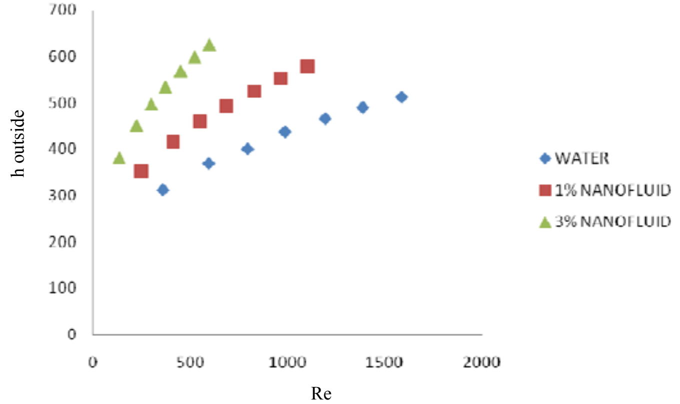

Figure 2. Reynolds no. *vs*. Heat transfer coefficient

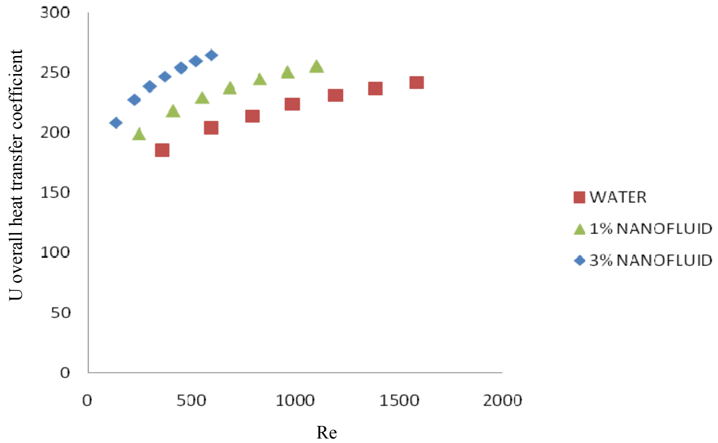

Figure 3. Re *vs*. overall heat transfer coefficient

From the Figure 3 it can be said that as the flow rate of cold fluid increases, overall heat transfer coefficient for outer surface of tube increases. In this case also increase in overall heat transfer coefficient is more in case of nanofluid than that with water.

For water and nanofluid

From the Figure 4 it can be said that as the time increases, temperature of cold water or nanofluid increases. In this case also increase in temprature is more in case of nanofluid than that with water.

For hot solution of magnesium sulfate

From the Figure 5 it can be said that as the time increases, temperature of magnesium sulfate solution decreases. In this case also decrease in temperature is more in case of nanofluid than that with water.

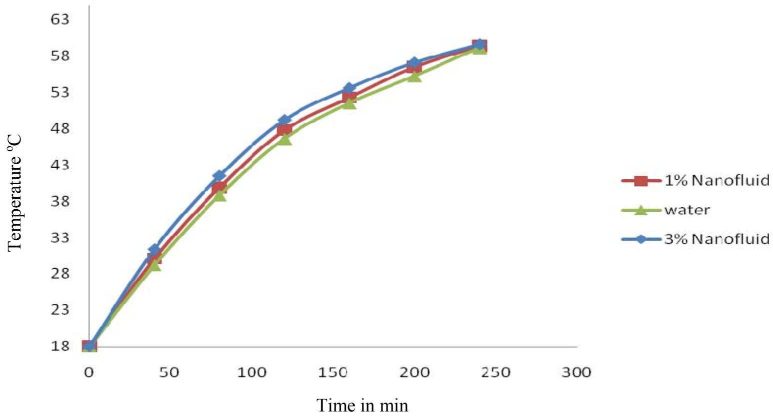

Figure 4. Time *vs.* temperature

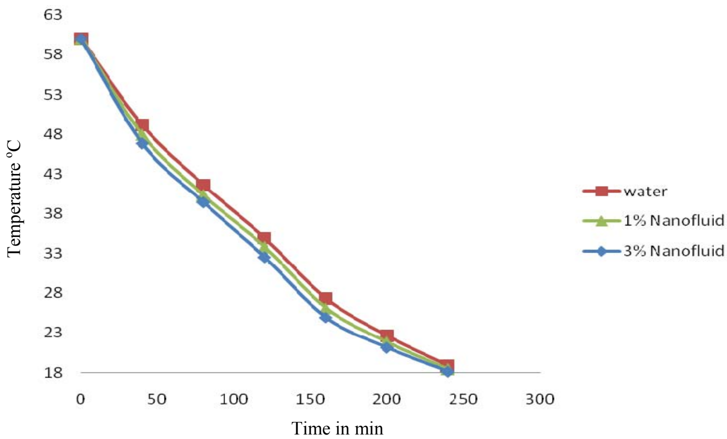

Figure 5. Time *vs.* temperature

Conclusion

The preparation of nanofluids was effectively made from copper oxide nanoparticles of different concentration of 1% and 3%. Magnesium sulphate which was used in crystallization process is also prepared to check the performance of nanofluids. Heat transfer coefficient is high with nanofluids as compared to without nanofluids and yield of crystallization is also large.

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