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Heat Transfer Enhancement in Heat Recovery Loops Using Nanofluids as the Intermediate Fluid

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In this paper, the effect of replacing water with various nanofluids as the heat transfer media in an industrial Heat Recovery Loop (HRL) have been modelled. Generally, nanofluids are prepared by distributing a nanoparticle through a base fluid such as water. Suspended nanoparticles slightly affect the thermal and physical properties of the base fluid. Primarily nanoparticles are added to improve the fluid's heat transfer characteristics by increasing its Reynolds number and thermal conductivity. Results show that by applying various HRL design methods and a nanofluid as an intermediate fluid, an increase in heat recovery is possible without the need for extra heat exchanger area and infrastructure. With the addition of 1.5 vol.% CuO nanoparticles to the HRL fluid using constant temperature storage method, heat recovery from liquid-liquid heat exchangers increases between 5 % and 9 %. In the case of air-liquid exchangers, the air-side heat transfer coefficient limits the impact of using a nanofluid. In other cases, the duty available from the process stream, such as a condenser, significantly restricts the heat transfer benefit of using a nanofluid. Alternative to increasing heat recovery, results show that applying a nanofluid in the HRL design phase enables heat exchanger area to decrease significantly for liquid-liquid matches.

1. Introduction

Different concepts and methods have been proposed to minimise energy use in process plants ranging from heat recovery systems for individual processes to total site integration. Along with other principles of Process Integration techniques, Pinch Analysis has been established as one of the most useful tools for analysing and optimizing energy systems of process plants. These standard techniques can be applied for targeting energy use and developing heat exchanger networks for single plants (Kemp, 2007). On a wider scale Total Site Integration offers energy conservation opportunities for sites with multiple processes and plants. Dhole and Linnhoff (1993) introduced the Total Site concept to describe a set of processes serviced by and linked through a central utility system. By considering inter-plant integration, Total Site Analysis has the potential to identify further energy savings.

By using an intermediate fluid such as steam or hot oil (for high temperature processes) or hot water (for low temperature processes) through a central utility system, indirect integration offers greater advantages of flexibility and process control but has a lower energy recovery target compared to direct integration. The intermediate fluid transfers excess heat from one plant to another. Thermal storage is needed to balance the instantaneous imbalances of the intermediate fluid flow between distinct processes. This system is called as Heat Recovery Loop (HRL) (Atkins et al., 2010). In recent years, several researchers have studied various parts of the design, operation and optimization of heat recovery loops, e.g. new thermal storage design by using a stratified tank (Walmsley et al., 2009), changing of storage temperature for seasonal production changes (Atkins et al., 2010), utilisation and sizing of thermal storage capacity (Atkins et al., 2012).

The conventional control system of a HRL measures and compares the outlet temperature of the loop fluid from each heat exchanger to a common hot or cold temperature set point. The flow rate of fluid through each heat exchanger is adjusted to achieve set point temperature. In this approach hot and cold storage

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temperatures are constant over time, thus this approach is called the constant temperature storage approach (CTS). An alternative approach to HRL control is varying the set point of the heat exchangers depending on their temperature driving force. This alternative approach is called variable temperature storage (VTS) due to mixing of different temperatures entering the tanks (Walmsley et al., 2013a). Walmsley et al. (2014) compared the two HRL control approaches to find the VTS system results in more effective distribution of temperature driving force between heat exchangers, lower average loop flow rates giving reduced pressure drop and pumping requirements, and increase in average temperature difference of hot and cold storage temperature, which increases thermal storage density and capacity.

Various techniques have been applied to increase heat transfer rates in heat exchangers and decrease heat and energy losses in process industries. These methods are known as Heat Transfer Enhancement (HTE). Generally speaking, HTE techniques are divided in two main groups: active techniques and passive techniques. In active techniques an external force is required (e.g. surface vibration, electrical or magnetic field, or acoustic move on fluid). Passive techniques, on the other hand, require no external forces. Rather it increases heat transfer by changing the surface geometry or by adding some additives to the fluid (Huminic and Huminic, 2012).

For many decades, adding solid particles to conventional fluids has been considered due to their high thermal conductivity. However, in practice, operational problems, such as fouling, sedimentation and increased pressure drop, occur by using these additives which dissuades industry from applying this type of HTE technique. In recent decades, progress in nanomaterials technology has made it conceivable to overcome these problem by producing particles at a nano-scale. Suspended nanoparticles in a fluid creates a new innovative category of fluids called nanofluids. Nanofluids are a class of fluids with a suspension of nano-sized particles, which aims to enhance a fluid's heat and mass transfer performance (Daungthongsuk and Wongwises, 2007). Water, ethylene glycol, transformer and turbine oil, and liquid paraffin are usually used as the base fluid, while metals and metal oxides such as Cu, CuO, Al_2O_3, SiO_2, TiO_2. The size of the nanoparticles are typically smaller than 100 nm.

In this paper the benefits of using a nanofluid as the heat transfer media in HRLs is investigated. Heat transfer correlations for nanofluids are reviewed from four recent papers. Various combinations of nanoparticles in water are examined to find which combination returns the best heat coefficient for the same vol. % of nanoparticles added. The selected nanofluid is then applied to replace the intermediate fluid in an industrial HRL model.

2. Literature review on nanofluids and their characteristics

Generally, in fluids, the effectiveness of heat transfer is described by the convective heat transfer coefficient, which is a function of a number of thermo-physical fluid properties, the significant ones being thermal conductivity, specific heat, viscosity and density.

2.1 Estimation of nanofluid thermo-physical properties

Nanofluid thermo-physical properties have been calculated by Eqs(1) to (4) from Khairul et al. (2014).

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \tag{1}$$

$$\mu_{nf} = (1+2.5\phi)\mu_{bf} \tag{2}$$

$$\frac{K_{nf} - K_{bf}}{K_{bf}} = 3.761088\phi + 0.017924T - 0.30734 \tag{3}$$

$$c_{p,nf} = \frac{(1-\phi)(\rho c_p)_{bf} + \phi(\rho c_p)_{np}}{\rho_{nf}} \tag{4}$$

Where ρ, μ, K and c_p are respectively density, viscosity, thermal conductivity and specific heat, ϕ is particle volume fraction (%), and T is the temperature in °C. Subscripts *np*, *bf* and *nf* are refer to nanoparticle, base fluid and nanofluid, respectively.

2.2 Nanofluid heat transfer coefficient correlations in literature

Several experimental and theoretical studies on the heat transfer coefficient of nanofluids in Plate Heat Exchangers (PHE) under a turbulent regime have been reported in literature. Khairul et al. (2014) illustrated that the heat transfer coefficient of CuO-Water nanofluid increased by 18 – 27 % compared to water. Their work was very similar to a previous study of the same nanofluid, which presented the following Nusselt number correlation (Pandey and Nema, 2012).

$$Nu = (0.26 + 0.2\phi - 0.0051\phi^2)Pe^{0.27} \quad 0.5 \le \phi \le 1.5 \tag{5}$$

Tiwari et al. (2013) investigated nanofluids made by using Al_2O_3, SiO_2, TiO_2 and CeO_2 nanoparticles. Their investigation showed the heat transfer coefficient of the nanofluid increased with increases in the volume flow rate of the non-nanofluid and nanofluid and with a decrease in the main fluid temperature (Tiwari et al., 2013). Tiwari et al. summarised their results using the following equation.

$$Nu = 0.348\,\mathrm{Re}^{0.663}\,\mathrm{Pr}^{0.33} \quad 0.5 \le \phi \le 3.0 \tag{6}$$

Eq (7) was developed by Pantzali et al. (2009) as they studied the efficiency of CuO-Water nanofluid with 4 vol.% of CuO nanoparticles as coolants in commercial PHE. According to their findings, the nature of coolant flow, e.g. turbulent flow, inside the heat exchanger play a significant role in the effectiveness of nanofluids.

$$Nu = 0.247\,\mathrm{Re}^{0.66}\,\mathrm{Pr}^{0.4} \quad \phi \le 4.0 \tag{7}$$

In the above equations, Nu, Pe, Re and Pr are Nuselt number, Peclet number, Reynolds number and Prantel number, respectively.

2.3 Nanofluid heat transfer coefficient calculation and results

CuO-Water, Al_2O_3-Water, SiO_2-Water and Cu-Water nanofluids have been initially investigated to find the best nanofluid for use in a HRL system. Several options of nanofluid and their impact on the heat transfer coefficient have been plotted in Figure 1. Figure 1A shows Cu-Water nanofluid tend to higher increase in convective heat transfer coefficient; however, at nano scale it is likely that Cu particles will oxidize in the vicinity of water. Therefore, for our purpose CuO-water nanofluid, the second best, has been chosen (Figure 1(a)). On the other hand, Eq(5) has a higher heat transfer coefficient increase for the CuO-Water nanofluid (Figure 1(b)).

The most important part of analysing nanofluid heat transfer enhancement is to find how much different correlations led to increase in heat transfer coefficient when compared to water. Figure 1B illustrated that according to Eq(5) percentage change in heat transfer coefficient increase up to 25 % at 1.5 vol.% in the nanofluid, while Eq(6) and Eq(7) show a linear increase by increasing of nanoparticle volume percentage in the nanofluid. Note that, Eq(5) limits ϕ up to 1.5 vol.%, in this correlation adding more nanoparticles in base fluid will cause reduction in Heat Transfer Coefficient (Pandey and Nema, 2012). All above led to select CuO-Water nanofluid with 1.5 vol.% of nanoparticle to observe 25 % increase in HRL intermediate fluid convective heat transfer coefficient.

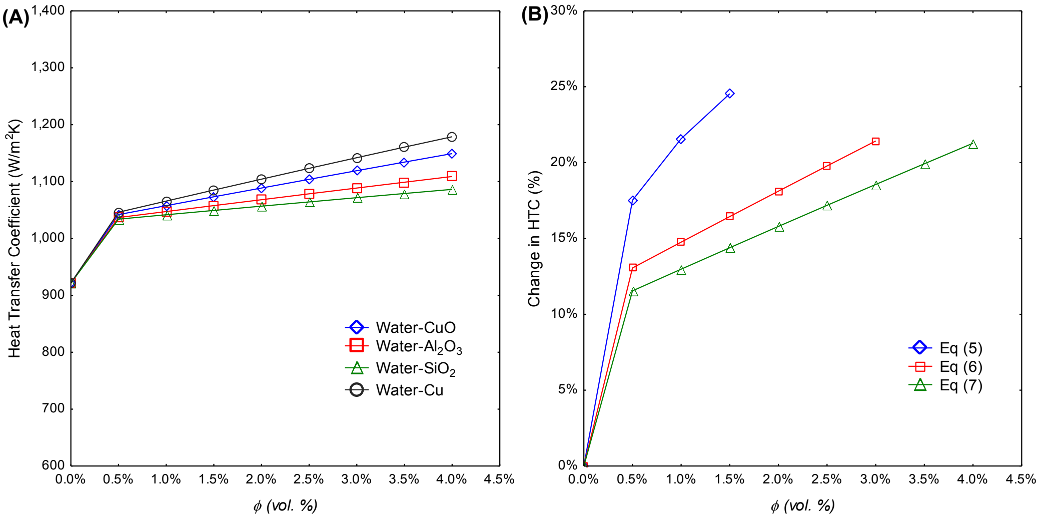

Figure 1: (a) Heat transfer coefficient vs. volumetric percentage of Water-CuO, Water-Al_2O_3, Water-SiO_2 and Water-Cu nanofluids using Eq(5), and (b) Comparison of heat transfer coefficient increase percentage vs. volumetric percentage of Water-CuO nanofluid for Eq(5), Eq(6) and Eq(7).

3. Methods

An Excel™ spreadsheet has been developed in order to calculate thermo-physical properties of nanofluids including their heat transfer coefficient using the method from Khairul et al. (2014). Table 1 shows the thermo-physical properties of the water, as base fluid, and water-CuO, as nanofluid, in HRL. An increase in density, thermal conductivity and viscosity values for the nanofluid as well as decrease in heat capacity is as expected. Adding 1.5 vol.% CuO nano-particles to water is estimated to increase the heat transfer coefficient by 25 % (Eq 5), from 4.00 kW/m^2.K to 5.0 kW/m^2.K.

Table 1: Thermo-physical properties of base fluid and nanofluid in HRL.

Fluid	ρ (kg/m^3)	C_p (kJ/kg.K)	K (W/m.K)	μ (kg/m.s^2)	h (kW/m^2.K)
Water	1,000.0	4.18	0.60	0.00100	4.0
Water-CuO	1,135.7	3.66	0.76	0.00106	5.0

The steady state ΔT_{min} HRL design method presented by Walmsley et al. (2013b), which is discussed further in detail in the Handbook of Process Integration (Klemeš, 2013), is applied for transient stream data analysis to calculate heat recovery. Four methods to operate and design a HRL have been applied based on methodologies presented by Walmsley et al. (2013a), these are:

i. Conventional design method with CST control.
ii. New VTS method of HRL design and operation.
iii. CTS method using water-CuO as intermediate fluid in HRL.
iv. VTS method using water-CuO as intermediate fluid in HRL.

The first two methods have been applied in previous works (Walmsley et al., 2013a) and results show that VTS method provides more heat recovery than CTS method. In this paper, the per cent increase in heat recovery for the two HRL design methods are compared to see if the one benefits more than the other.

4. Heat recovery loop with nanofluid case study

4.1 Dairy Factory Case study

A large multi-plant dairy factory has been chosen as a case study. The existing HRL is using water as the intermediate fluid. The factory consists of eight separate semi-continuous plants that share common utility, powder and materials handling services. Plants have been investigated and integrated to industry best practice. A HRL was installed as a dedicated indirect heat recovery to increase inter-plant heat integration. For further improvement in the HRLs performance is desired and modifying intermediate fluid (water) to become nanofluid is investigated.

4.2 Data extraction

Process streams from each plant connected to the HRL are presented in Table 2, which T_s and T_t are supply and target temperatures, and CP represents heat capacity flow rate. The data is taken from Walmsley et al. (2014) where the full transient characteristics are presented.

Table 2: Extracted Stream data

Stream	Type	T_s (°C)	T_t (°C)	CP (kW/K)
Dryer Exhaust A	Hot	75	55	139
Dryer Exhaust B	Hot	75	55	73
Dryer Exhaust C	Hot	75	55	44
Dryer Exhaust D	Hot	75	55	28
Utility Unit A	Hot	45	30	8
Utility Unit B	Hot	45	30	8
Casein A	Hot	50	20	22
Casein B	Hot	50	20	32
Casein C	Hot	50	20	32
Condenser	Hot	80	79	351
Cheese A	Hot	35	20	98
Cheese B	Hot	35	20	114

Stream	Type	T_s (°C)	T_t (°C)	CP (kW/K)
Site Hot Water	Cold	16	65	160
Milk Treatment A	Cold	10	50	104
Milk Treatment B	Cold	10	50	104
Milk Treatment C	Cold	11	50	116
Whey A	Cold	12	45	16
Whey B	Cold	14	45	9

4.3 Results and discussion

The increase of heat recovery as result of applying each design and control procedure is presented in Figure 2. Adding nanofluid to the original intermediate fluid, i.e. water, in the CTS method a wide range of variation in increased heat recovery for the process streams on the HRL. The highest increase is in Whey B with 9 % increase and lowest increase is shown in Casein plants, especially Casein B with 5.1 % increase. For hot streams Cheese A* and B*, in case of the CTS method, the hot loop temperature is greater than the stream's supply temperature, and therefore heat recovery is not allowed under the CTS approach. For Dryer Exhaust A, B, C, and D a very small increase is observed, which indicates the air side is the limiting heat transfer coefficient. Also, Utility A and B and Condenser have fixed duties and so increasing the heat transfer coefficient does not impact on heat recovery.

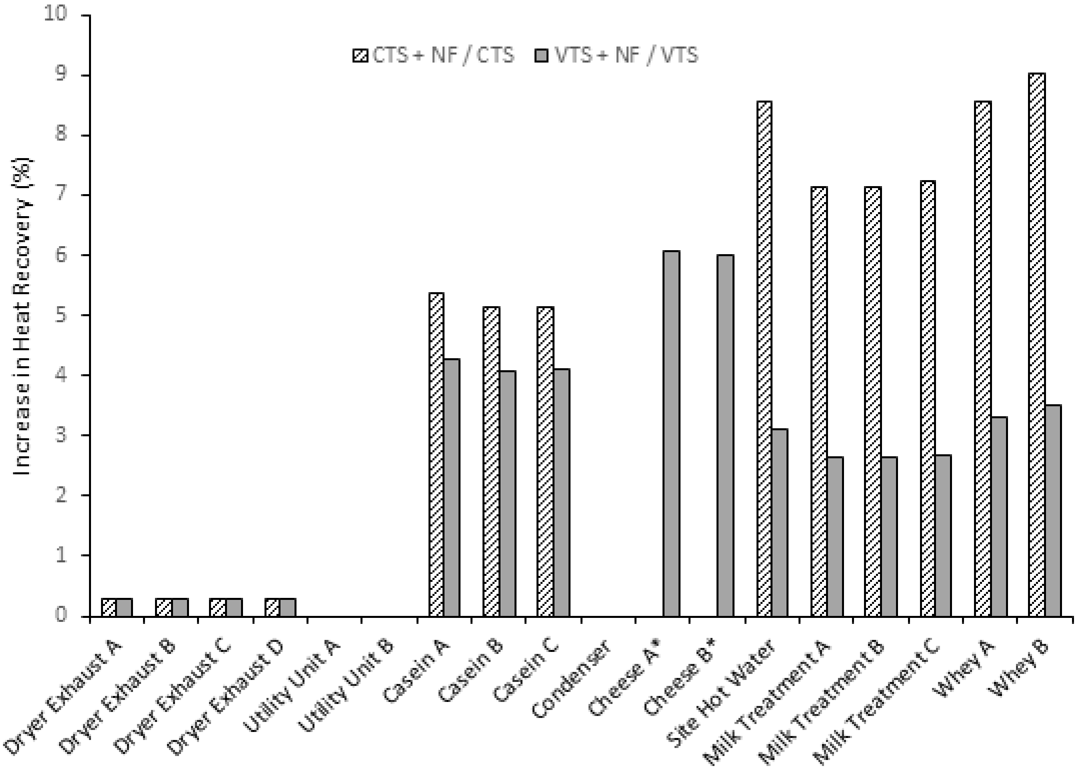

Figure 2: Heat recovery increase in each process heat exchanger, comparison between (CTS+NF)/CTS and (VTS+NF)/ VTS.

In the case of applying VTS and VTS with nanofluid methods, again a wide range of differences in increase of heat recovery appears. In this case, Cheese A shows highest heat recovery increase with 6 % while Milk Treatment A and B have the lowest increase, 2.6 %. Moreover, it shows a small change in heat recovery for Dryer Exhaust A, B, C, and D and again hot utilities which are condenser, Utility A, and Utility B remain constant due to their fixed duty. Average increase of heat recovery for the entire factory is about 4% in the case of CTS with nanofluids and 2.5 % in the case of VTS with nanofluids. Liquid-liquid heat exchangers, exclusively, shows 7 % and 4 % increase respectively for CTS and VTS with nanofluids. The differences in the increases in heat recovery between the streams is due to different stream characteristics, flow rates, and heat exchanger types and geometries. If a nanofluid and its enhanced heat transfer coefficient were applied in the design process to obtain the same duties as the original design without nanofluids, total heat exchanger area decreases as given in Table 3. Liquid–liquid matches show a decrease in area of 10 % whereas the decrease in area for gas-liquid matches is negligible. This causes a reduction in capital investment for the heat recovery system and site. Future work will look at the impact of using a nanofluid on the pressure drop and pumping power required for the HRL.

Table 3: Comparison of reduction in area for different matches

Match Type	Reduction in Area (%)
Gas - Liquid	0.3
Vapour - Liquid	7.5
Liquid - Liquid	10.0

5. Conclusions

Adding 1.5 vol.% CuO to the intermediate fluid of a HRL shows an increase in heat recovery of whole plant. Results show that by applying various HRL design methods accompanied by using nanofluid as an intermediate fluid is desirable way of achieving significant heat recovery without the need for extra heat exchanger area and infrastructure. In the case of air-liquid exchangers, it is clear that the air side heat transfer coefficient plays a significant role in controlling the overall heat transfer coefficient and in utility and condenser streams no changes in heat recovery are observed because they are a fixed duty. Alternative to increasing heat recovery, results show that by using nanofluid as intermediate fluid of HRL total heat exchanger area in the HRL for liquid- liquid heat exchangers decreases significantly.

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