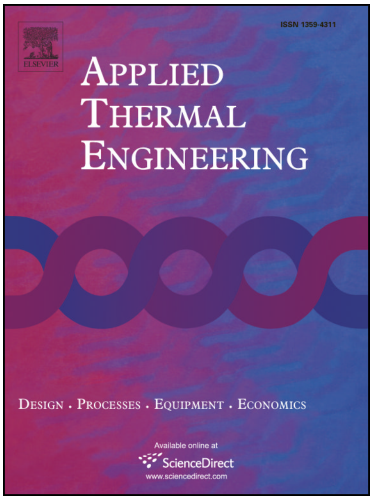

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PII: S1359-4311(17)35770-8
DOI: https://doi.org/10.1016/j.applthermaleng.2018.01.114
Reference: ATE 11768

To appear in: *Applied Thermal Engineering*

Received Date: 5 September 2017
Revised Date: 28 January 2018
Accepted Date: 29 January 2018

Please cite this article as: T. Laukkanen, A. Seppälä, Interplant heat exchanger network synthesis using nanofluids for interplant heat exchange, *Applied Thermal Engineering* (2018), doi: https://doi.org/10.1016/j.applthermaleng.2018.01.114

Interplant heat exchanger network synthesis using nanofluids for interplant heat exchange

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Abstract

Heat transfer between different processes or inter-plant heat integration can be seen as an efficient way to cost-efficiently improve the energy efficiency of a system of different processes. Nanofluids are a new type of heat transfer fluids, in which particles with size of 1-100 nm are suspended in a liquid. Nanosized particles can cause considerable enhancement in convective heat transfer performance of the base fluid, although at the same time they increase the viscosity of the fluid, thus enhancing the needed pumping power. In this work we study the effect of using nanofluids in streams transferring heat from different processes by optimizing the total annual cost of a heat exchanger network. These costs include the cost of hot and cold utilities, heat exchanger investment costs and pumping costs. A modified version of the well-known Synheat superstructure is used as the optimization model in comparing the different fluids (water and five nanofluids) in two examples. Some key parameters (electricity price and annuity factor) are varied in these two examples. The results show that nanofluids can in some cases save total annual costs and especially if electricity prices are low compared to other factors. This is true especially for MgO 1.0% which outperformed water and the other nanofluids in normal price conditions. But altogether it is evident that most, and in some cases all, of the benefits provided by nanofluids to improved heat transfer is canceled out by the increased pressure drops.

Keywords: heat exchanger network synthesis, Synheat model, process integration, MINLP, grouping of process streams, nanofluid

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1. Introduction

One way of improving energy efficiency in industrial processes is by increasing heat integration. Typically different processes or process parts have their own specific processing tasks. These processes can be heat integrated in order to improve the energy efficiency of the entire system and to increase the overall economic efficiency of the total system and the individual processes. In heat integration between processes the process

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streams existing in an overall system are grouped into their own processes and heat integration between streams in the same group can be prioritized against heat integration between streams in different groups. This type of heat integration is called inter-plant heat integration. Otherwise heat integration between processes is similar to normal heat integration where the objective is to develop heat exchanger networks that minimize the annual energy and investment costs. The heat integration between processes can be accomplished directly or indirectly. The streams that transfer heat between process streams are called intermediate streams.

Because intermediate streams are used purely as a heat transfer media, these should transfer heat as efficiently as possible. For this reason fluids that have high heat transfer coefficients and low viscosity in order to decrease the pressure-drop are optimal as intermediate streams. Naturally these properties are hard to find in a single fluid, and thus the choice of the optimal fluid is a compromise between the properties. Nanofluids have been an active research area because they provide increased heat transfer coefficients. Unfortunately they also typically increase pressure drop.

Nanofluids are a new type of heat transfer fluids, in which particles with size of 1-100 nm are suspended in a liquid. Most typically the particles are solid (Gupta et al. (2014) and Yu et al. (2012)), however recently also liquid phase nanoparticles (nanoemulsions) (Saarinen et al., 2015) as well as phase changing nanoparticles (Xu et al. (2015), Puupponen et al. (2015), Mikkola et al. (2017) and Trinh and Xu (2017)) have been investigated. Many studies have demonstrated that the addition of the nanosized particles can cause considerable enhancement in convective heat transfer performance of the base fluid. However, an adverse effect of the particles is that they increase the viscosity of the fluid, thus enhancing the needed pumping power (Mikkola et al., 2018). In most of the nanofluid studies the overall benefit, accounting for both heat transfer and the pressure loss enhancement, has not been properly investigated. For the purpose of the present study, we have chosen from literature five different type of water-based nanofluids, of which structure, heat transfer and pressure loss characteristics are well documented.

Heat integration between plants or processes, or inter-plant heat exchanging as it is nowadays called, has been studied by many authors. Methods to solve the problem were first based on thermodynamics. In the minimum energy network approach by Ahmad and Hui (1991) the designer can decide if the inter-plant heat exchanging is considered directly by process streams or indirectly with intermediate streams. Later the authors continued (Hui and W. Ahmad, 1994a) the work so that heat transfer cost calculations are considered and in still so that different steam pressure levels are used to exchange heat indirectly between processes (Hui and W. Ahmad, 1994b). This idea of using different levels of steam as the intermediate streams was continued by Dhole and Linnhoff (1993). In their approach only surplus heat found by using Grand Composite Curves could be transferred to other processes. Amidpour and Polley (1997) modified the Problem Table algorithm for heat integrating different process parts. Rodera and Bagajewicz (1999) and Bagajewicz and Rodera (2000)) developed an approach where processes can be heat integrated directly using process streams or indirectly using intermediate streams that don't have to be isothermal. A three-step mathematical programming approach to solve inter-plant heat exchanging was developed by Kralj et al. (2005), where the waste heat of internally heat integrated individual processes are integrated between each other in order to improve the total annual cost of the overall system.

Laukkanen et al. (2012a) presented a method for simultaneous synthesis of heat exchanger networks which allows direct heat transfer between streams in the same process and both direct and indirect heat transfer between process streams in other processes. The annual costs of energy and capital are considered simultaneously. Nemet et al. (2015) continued the work with increased realism, but also with increased model complexity. The developed model for indirect heat transfer between processes considers pressure level optimization for intermediate utilities and indirect heat transfer between processes, heat losses through pipeline, preheating of unrecovered condensate, pipeline design including pipe diameter, pipe thickness, insulation thickness and pipeline layout as well as utility prices that are fore-casted. Chang et al. (2017b) developed a method and a superstructure for multiplant heat exchanger network synthesis including piping, pumping, heat exchanger and utility cost in optimizing the total annual cost. In their approach heat can be transferred directly between processes using process streams. Chang et al. (2017a) continued that work by using intermediate fluid circles as the way to transfer heat between processes. Tarighaleslami et al. (2017) and Song et al. (2016) developed new targeting methods for heat transfer between processes.

In Laukkanen and Fogelholm (2011) and Laukkanen et al. (2012b) the presented methods also has stream grouping into subprocesses, but the grouping is not based on streams physically existing in the same process but is done for increased calculation efficiency. Additionally no intermediate streams exist. Lately improvements for general heat exchanger network synthesis has been proposed by (Bonhivers et al. (2017a), Bonhivers et al. (2017b), Nunez-Serna and Zamora (2016)), but no special attention to different processes have been given.

Lately Hipólito-Valencia et al. (2014) presented a superstructure for heat integration of an eco-industrial park where both intra and inter-plant heat exchange for the process streams is allowed and additionally for low-temperature waste heat utilization, a set of organic Rankine cycles (ORCs) can be integrated inside the eco-industrial park. Wang and Feng (2017) studied factors that can affect the final design of pipelines between plants and connection patterns for interconnectivity of individual plants in an area. Cheng et al. (2014) presented a game-theory approach for the interplant heat exchanging problem by using a sequential strategy that allows every plant to maximize its own financial benefit at every step while simultaneously striving for the largest cost saving for the entire site.

In this work five different nanofluids are compared with water in order to understand and verify their possibilities in acting as fluids in heat integration between processes. A MINLP model based on the Synheat model is used to compare the total annual cost of using these different fluids as intermediate streams exchanging heat between different processes. In the model process streams can exchange heat with streams in the same process and with intermediate streams that can be used to transfer heat into other processes. Heat transfer between processes are only allowed with intermediate streams. The intermediate streams are basic process streams that need to be heated or cooled. Thus the novelty in this work is in comparing different carefully chosen nanofluids acting as heat transfer media in interplant heat exchanging and in studying how beneficial this inter-plant heat exchanging is in general.

The rest of this paper is organized as follows. Next in Section 2 the optimization model for simultaneous heat exchanger network synthesis inside and between processes is presented. The model is based on the Synheat model from Yee and Grossmann (1990). Additionally the five nanofluids are presented. In Section 3 two HENS = Heat Exchanger Network Synthesis examples are optimized with the model and with six (water + five nano) fluids acting as intermediate streams. Couple of key input parameters (electricity cost and annuity factor) are varied in order to validate the results. Finally in Section 4 the main conclusions are given.

2. Model and fluids

The stagewise superstructure proposed by Yee and Grossmann (1990) is used as the basis for modeling. An example of a superstructure having two hot streams and two cold streams is given in Figure 1. In this work the superstructure is modified by giving an additional index indicating into which process a stream belongs to. The intermediate streams are streams that can be either hot or cold process streams, and these can be present in all processes and can transfer heat between processes. Otherwise these intermediate streams are normal process streams that need to be heated or cooled. All streams can be chosen as intermediate streams, if the process stream has only water in it. User of the model can decide which streams can act as intermediate streams. Hot and cold utilities can be used for all streams. Temperatures of streams in each stage are the optimized variables. The objective function i.e. total annual cost of the network is dependent on the stage temperatures of each stream. Unlike in the basic model from Yee and Grossmann (1990), in this model additionally the pressure drops in heat exchangers and the related electricity consumption is optimized. The pressure drops are obtained from literature. Pressure drops in the pipeline have not been included nor the cost of adding nano material to the fluid when intermediate fluid includes nano material. Lack of pipeline pressure drop has not been considered, because these costs can be made so much smaller compared to pressure drops in heat exchangers by increasing the pipe diameter. For example with the same mass flow, the pressure drops of a pipeline of 1000 m length having a diameter of 20 cm, are only 0.3% of that in a heat exchanger having an area of $1m^2$ and diameter of 8 cm. Nano material costs are not included, because these are still in development phase and the costs of these for an industrial customer buying large batches, was not available.

2.1. Indexes and sets

Tables 1 and 2 provides the indexes and sets needed in the model.

Table 1: Indexes needed in model

Index	*Description*
i	hot process stream
j	cold process stream
k	temperature location in superstructure (1,...,NOK+1)
g	group
f	fluid
hu	hot utility
cu	cold utility

2.2. Parameters

Table 3 provides the parameters needed in the model.

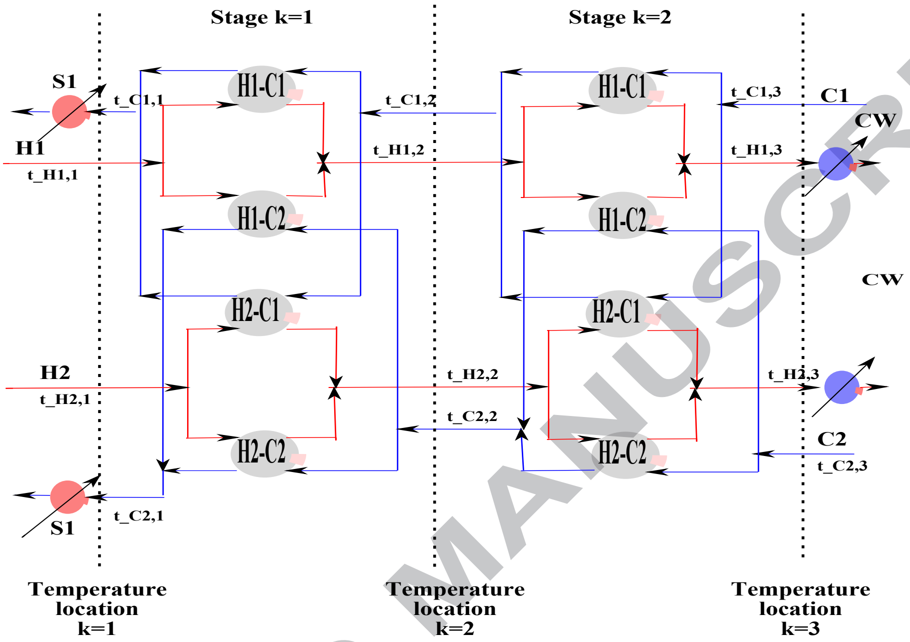

Figure 1: Synheat superstructure for two hot and two cold process streams.

2.3. Variables

Table 4 provides the variables needed in the model.

2.4. Model equations

The following chapters provide all the equations needed in the model.

2.4.1. Heat balance of streams

Equations 1 to 2 give the overall heat balance of process streams.

$$\sum_{st \in ST} q_{i,j,k} = FCp_i \cdot (TIN_i - TOUT_i) \tag{1}$$

$$\sum_{st \in ST} q_{i,j,k} = FCp_j \cdot (TIN_j - TOUT_j) \tag{2}$$

2.4.2. Heat balance of stages of each process stream

Equations 3 to 6 give the heat balance of stage of each process streams and the utility consumption.

Table 2: Sets needed in model

Set	*Description*
I	$= \{i \,|\, i$ is a hot process stream$\}$
J	$= \{j \,|\, j$ is a cold process stream$\}$
HU	$= \{hu \,|\, hu$ is a hot utility$\}$
CU	$= \{cu \,|\, cu$ is a cold utility$\}$
ST	$= \{k \,|\, k$ is a stage and temperature location in superstucture$\}$
$FIRST$	$= \{k \,|\, k$ first temperature location in superstucture$\}$
$LAST$	$= \{k \,|\, k$ last temperature location in superstucture$\}$
G	$= \{g \,|\, g$ is a group$\}$
F	$= \{f \,|\, f$ is a fluid$\}$
AGI	$= \{(i,g) \,|\, I \cap G$ all hot streams in all groups$\}$
GI	$= \{(i,g) \,|\, I \cap G$ hot streams in a group$\}, GI \subset= AGI,$
AGJ	$= \{(j,g) \,|\, J \cap G$ all cold streams in all groups$\}$
GJ	$= \{(j,g) \,|\, J \cap G$ cold streams in a group$\}, GJ \subset= AGJ,$

$$\sum_j q_{i,j,k} = FCp_i \cdot (th_{i,k} - th_{i,k+1}) \tag{3}$$

$$\sum_i q_{i,j,k} = FCp_j \cdot (tc_{j,k} - tc_{j,k+1}) \tag{4}$$

$$qc_i = FCp_i \cdot (th_{i,k} - TOUT_i), \quad k \in LAST \tag{5}$$

$$qh_j = FCp_j \cdot (TOUT_j - tc_{j,k}), \quad k \in FIRST \tag{6}$$

2.4.3. Start and end temperatures

Equations 7 to 8 define the correct start and end temperatures for streams.

$$TIN_i = th_{i,k}, \quad k \in FIRST \tag{7}$$

$$TIN_j = tc_{j,k}, \quad k \in LAST \tag{8}$$

2.4.4. Monotonic decrease in stage temperatures

Equations 9 to 12 define that stage temperatures decrease monotonically.

$$th_{i,k} >= th_{i,k+1} \tag{9}$$

$$tc_{j,k} >= tc_{j,k+1} \tag{10}$$

$$th_{i,k} >= TOUT(i), \quad k \in LAST \tag{11}$$

$$tc_{i,k} <= TOUT(j), \quad k \in FIRST \tag{12}$$

2.4.5. Existence of heat exchangers and temperature difference in each side

Equations 13 to 19 define the temperature difference on each side of a heat exchanger.

$$q_{i,j,k} - min(E_i, E_j) \cdot z_{i,j,k} <= 0 \tag{13}$$

$$dt_{i,j,k} <= th_{i,k} - tc_{j,k} + GAMMA_{i,j} \cdot (1 - z_{i,j,k}) \tag{14}$$

$$dt_{i,j,k+1} <= th_{i,k+1} - tc_{j,k+1} + GAMMA_{i,j} \cdot (1 - z_{i,j,k}) \tag{15}$$

Table 3: Parameters in models

Parameter	*Description*	emphUnit
TIN	Starting temperature of stream (process, utility)	[K]
$TOUT$	End temperature of stream (process, utility)	[K]
FCp	Heat capacity flow rate of streams (process, utility)	$[\frac{kW}{K}]$
H	Heat transfer coefficient of streams (process, utility)	$[\frac{kW}{K}]$
E	Heat content of streams (process, utility)	$[kW]$
$UNITC$	Fixed cost of a heat exchanger	$[\frac{€}{m^2}]$
$HUCOST$	Cost of hot utility	$[\frac{€}{kW}]$
$CUCOST$	Cost of cold utility	$[\frac{€}{kW}]$
$ACOEFF$	Cost parameter for heat exchanger area	$[\frac{€}{m^2}]$
$BETA$	Scale-of-economics parameter for area	$[-]$
$GAMMA$	upper bound of driving force between streams	$[-]$
M	Big number	$[-]$
NOK	Number of stages	$[-]$
$Tmapp$	Minimum approach temperature	$[K]$
$PRESSFACT$	The pressure drop factor relative to water	$[-]$
$HFACT$	The heat transfer coefficient factor relative to water	$[-]$
ANN	Annuity factor	$[-]$
$DPRESS$	Pressure drop of water per heat transfer area	$[\frac{kPa}{m^2}]$
EFF	Pump isentropic efficiency (0.8)	$[-]$
ROO	Density	$[\frac{kg}{m^3}]$
CP	Heat capacity	$[\frac{kJ}{kg*K}]$
$ELCOST$	Electricity cost	$[\frac{€}{kW}]$

$$qc_i - E_i \cdot zcu_i <= 0, \tag{16}$$

$$qh_j - E_j \cdot zhu_h <= 0, \tag{17}$$

$$dthu_j <= TOUT_{hu} - tc_{j,k}, \quad k \in FIRST \tag{18}$$

$$dtcu_i <= th_{i,k} - TOUT_{cu}, \quad k \in LAST \tag{19}$$

2.4.6. Logaritmic mean temperature difference

Equations 20 to 22 define that the approximations for logarithmic mean temperature difference of heat exchangers based on the work by Shenoy and Fraser (2003).

$$lmtdij_{i,j,k} = (0.5 \cdot (dt_{i,j,k}^{0.3275} + dt_{i,j,k}^{0.3275}))^{\frac{1}{0.3275}} \tag{20}$$

$$lmtdhuj_j = (0.5 \cdot ((TIN_{hu} - TOUT_j)^{0.3275} + dthu_j^{0.3275}))^{\frac{1}{0.3275}} \tag{21}$$

$$lmtdicu_i = (0.5 \cdot ((TOUT_i - TIN_{cu})^{0.3275} + dtcu_i^{0.3275}))^{\frac{1}{0.3275}} \tag{22}$$

2.4.7. Area

Equations 23 to 25 define the heat exchanging surface area.

Table 4: Variables in models

Variable	*Description*	*Unit*	*Variable type*
$th_{i,k}$	Temperature of hot stream i entering stage k	[K]	Positive
$tc_{j,k}$	Temperature of cold stream j entering stage k	[K]	Positive
$q_{i,j,k}$	Energy exchanged between i and j in k	[kW]	Positive
qcu_i	Energy exchanged between i and the cold utility	[kW]	Positive
qhu_j	Energy exchanged between j and the hot utility	[kW]	Positive
$dt_{i,j,k}$	Approach temperature between i and j at k	[K]	Positive
$dtcu_i$	Approach temperature between i and the cold utility	[K]	Positive
$dthu_j$	Approach temperature between j and the hot utility	[K]	Positive
$lmtdij_j$	Log mean temperature difference in a match	[K]	Positive
$lmtdhuj_j$	Log mean temperature difference in a match	[K]	Positive
$lmtdicu_i$	Log mean temperature difference in a match	[K]	Positive
$a_{i,j,k}$	Heat transfer area	[K]	Positive
ahu_j	Heat transfer area	[K]	Positive
acu_i	Heat transfer area	[K]	Positive
$hexcost$	Area related cost of a heat exchanger	[€]	Positive
$unitcost$	Fixed cost of a heat exchanger	[€]	Positive
$utilitycost$	Cost of hot and cold utilities	[€]	Positive
$powi_i$	Power needed for pressure drop of i	[kW]	Positive
$powj_i$	Power needed for pressure drop of j	[kW]	Positive
$powcu_i$	Power needed for pressure drop of i	[kW]	Positive
$powhu_j$	Power needed for pressure drop of j	[kW]	Positive
$powercost$	Total cost of power	[€]	Positive
$z_{i,j,k}$	Existence of a match	[-]	Binary
zcu_i	Existence of a match	[-]	Binary
zhu_j	Existence of a match	[-]	Binary
$cost$	Total annual cost of network	[€]	Free

$$a_{i,j,k} = \sum_{i,j,k}\left(\frac{q_{i,j,k}\cdot(\frac{1}{H_i}+\frac{1}{H_j})}{lmtdij_{i,j,k}}\right) \tag{23}$$

$$ahuj = \sum_{j}\left(\frac{qhu_j\cdot(\frac{1}{H_j}+\frac{1}{H_{hu}})}{lmtdjhu_j}\right) \tag{24}$$

$$acu_i = \sum_{i}\left(\frac{qcu_i\cdot(\frac{1}{H_i}+\frac{1}{H_{cu}})}{lmtdicu_i}\right) \tag{25}$$

2.4.8. Costs

Equations 26 to 29 define costs for different issues.

$$unitcost = UNITC \cdot \sum_{i,j,st} z_{i,j,st} + UNITC \cdot \sum_{i} zcu_i + UNITC \cdot \sum_{j} zhu_j \tag{26}$$

$$hexcost = ACOEFF \cdot a_{i,j,k}^{BETA} + HUCOEFF \cdot ahu_j^{BETA} + CUCOEFF \cdot acu_i^{BETA} \tag{27}$$

$$utilitycost = HUCOST \cdot \sum_{j} qh_j + CUCOST \cdot \sum_{i} qc_i \tag{28}$$

$$powcost = ELCOST \cdot (\sum_{i} (pow_i + powcu_i) + \sum_{j} (pow_j + powhu_j)) \tag{29}$$

2.4.9. Power consumption

Equations 30 to 33 define the power consumption of streams.

$$pow_i = \sum_{j,k} \frac{PRESSFACT_f \cdot DPRESS \cdot EFF \cdot a_{i,j,k}}{ROO} \tag{30}$$

$$pow_j = \sum_{i,k} \frac{PRESSFACT_f \cdot DPRESS \cdot EFF \cdot a_{i,j,k}}{ROO} \tag{31}$$

$$powcu_i = \frac{PRESSFACT_f \cdot DPRESS \cdot EFF \cdot acu_i}{ROO} \tag{32}$$

$$powhu_j = \frac{PRESSFACT_f \cdot DPRESS \cdot EFF \cdot ahu_j}{ROO} \tag{33}$$

2.4.10. Objective function

Equations 34 defines the objective function of the model.

$$cost = unitcost + hexcost + utilitycost + powcost \tag{34}$$

2.5. Fluids

Table 6 gives data of the different fluids that have been studied. We have selected five different water-based nanofluids with well characterized structures. These fluids are based on three different nanoparticle materials, different particle sizes and concentrations (Table 5). For all chosen nanofluids, both the heat transfer coefficients and the pressure losses have been measured in a circular pipe. Table 6 presents averaged values of heat transfer coefficient and pressure losses within Reynolds number range 4000-9000, i.e. the values correspond to turbulent flow. The information is obtained from Duangthongsuk and Wongwises (2010) relating to nanofluids TiO_2 0.6% and TiO_2 1.0% , from Esfe et al. (2014) relating to MgO 1.0% and Meriläinen et al. (2013) related to nanofluids SiO_2 1.0% and SiO_2 4.0% .

Figures 2 and 3 show the HFACT (heat transfer coefficient of fluid divided by heat transfer coefficient of pure water) and PRESSFACT (pressuredrop of fluid divided by pressure drop of pure water) as a function of the Reynolds number obtained experimentally. Base on this data, a single average value for each fluid is obtained.

Several studies on different types of nanofluids (e.g. Meriläinen et al. (2013), Saarinen et al. (2015), Mikkola et al. (2017) and Mikkola et al. (2018)) have shown that the overall heat transfer efficiency (heat transfer and pressure losses are both accounted for) in forced convection heat transfer decreases when the concentration of particles increases. Therefore, we have choses mostly relatively low concentration fluids, and added as a reference one fluid having a higher concentration (SiO_2 4.0%).

Table 5: List of characteristics of the nanofluids studied.

Particle material	Particle size, average [nm]	Concentration of particles [$vol\%$]
TiO_2	21	0.6
TiO_2	21	1.0
MgO	40	1.0
SiO_2	28-110[1]	1.0
SiO_2	28-110[1]	4.0

[1] The particle size diameter was widely distributed. Size distribution peak at 60 nm.

Table 6: Fluid characters.

Fluid	DPRESS [$\frac{kPa}{m^2}$]	ROO [$\frac{kg}{m^3}$]	PRESSFACT [−]	HFACT [−]
Water	80.74	1000	1.000	1.000
TiO_2 0.6%	80.74	1000	1.129	1.145
TiO_2 1.0%	80.74	1000	1.278	1.264
MgO 1.0%	80.74	1000	1.100	1.255
SiO_2 1.0%	80.74	1000	1.375	1.284
SiO_2 4.0%	80.74	1000	2.114	1.463

3. Results and discussion

The model is used to compare the different fluids in two examples.

3.1. Small example

First the model is used to optimize a small example. The data of the small example is given in Table 7, which also shows which streams are in which processes. The example is not from literature nor from the industry, but the cost parameters are obtained from Kralj et al. (2005). The problem has four hot process streams and four cold process streams that are in two different processes. T_{mapp} for all heat exchangers is 1. Number of stages is equal to 2. The model is solved with six different fluids and the electricity cost (108 and 36 $\frac{€}{kW}$) and the annuity factor are varied (0.192072 and $2 \cdot 0.192072$) for each fluid. The point of varying the electricity cost and the annuity factor was to perform sensitivity analysis for the results because these input parameters reinforces the effect of pressure drop and heat transfer efficiency. The change in the cost of electricity should make pressure drop considerations more important and the change in annuity factor should make the heat transfer area or heat transfer in general more important. These two issues are the ones we are trying to influence with nano fluids. The cost of electricity of 36 €/MWh is a common cost for industrial electricity user and although 108 €/MWh is an arbitrary choice, it is clearly bigger than 36 so that the effect of pressure drop is clearly seen. The annuity factor 0.192072 is typical for energy efficiency investments, and although $2 \cdot 0.192072$ is an arbitrary choice, it is clearly bigger than 0.192072 so that the effect of heat transfer efficiency is clearly seen.

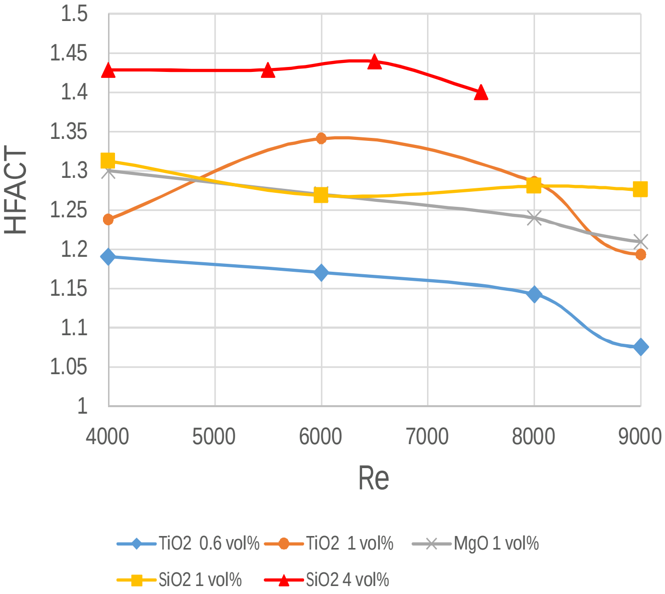

Figure 2: HFACT as a function of the Reynolds number for different nanofluids.

Additionally there is a reference case, where no heat exchange between processes is allowed. Regardless if a stream is acting as an intermediate stream or not, each stream needs to be heated or cooled to its target temperature. Now if there is no heat transferred between processes even though it is possible, this indicates that interplant heat exchanging is not economical, and the heating of the intermediate stream is done inside a single process. Then the total annual costs should be exactly the same (remembering that non-convex problems solved with an algorithm that is able to provide only locally optimal solutions) in both cases when the chosen intermediate stream is pure water.

Hot stream 4 and cold stream 4 are the intermediate streams that are allowed to transfer heat also between different processes. In the model the reference case (no heat exchanging between groups is allowed) is arranged so that both hot stream 4 and cold stream 4 (the possible intermediates streams in other cases) are only in group 1, so these can't exchange heat with streams in group 2. ELP=A stands for electricity cost $108\frac{€}{kW}$ and ELP=B stands for electricity cost $36\frac{€}{kW}$. ANN=A stands for annuity factor 0.192072 and ANN=B for annuity factor $2 \cdot 0.192072$.The problems are solved with GAMS (Brook et al., 2008). The MINLP solver used together with GAMS is DICOPT[1]. The NLP solver

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[1] Engineering Design Research Center (EDRC) at Carnegie Mellon University

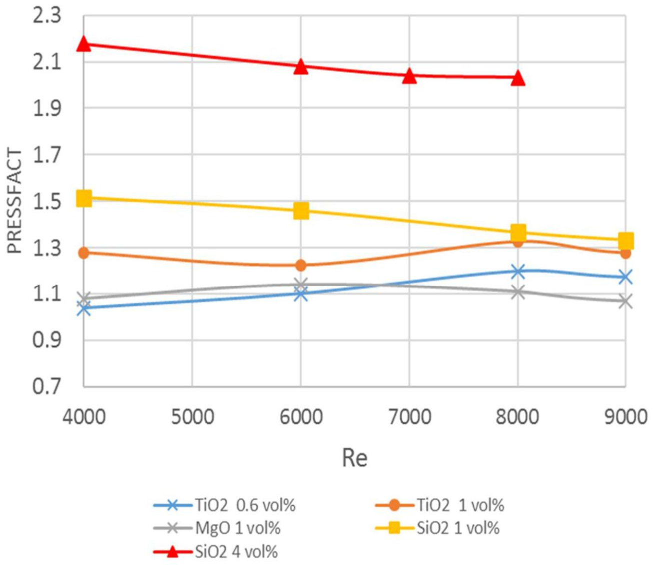

Figure 3: PRESSFACT as a function of the Reynolds number for different nanofluids.

used in Dicopt is CONOPT3[2] and the MILP solver is CPLEX[3].

The main results of all cases are shown in Table 8.

3.1.1. Electricity price normal and investment cost normal, (ElP=A,ANN=A)

When comparing the cases when electricity price and investment costs are normal (ElP=A,ANN=A), it is clear that

- Interplant heat exchanging is beneficial
- All nanofluids provide small possibilities for cost reductions compared to water
- MgO 1.0% is slightly the best fluid
- Integration in general and designing the heat exchanger network is much more important that finding the optimal heat transfer material

The best network for this case, which is MgO 1.0% , is presented in Figure 4. All networks are presented in the Supplementary material.

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[2] ARKI Consulting and Development A/S

[3] ILOG CPLEX Division

Table 7: Process data for small example.

Stream	TIN [°C]	TOUT [°C]	FCp [$\frac{kW}{^\circ C}$]	H [$\frac{kW}{m^2 \cdot {}^\circ C}$]	Process
H1	155	30	8.0	2	1
H2	80	40	15.0	2	2
H3	200	40	15.0	2	2
H4	210	30	15.0	fluid	1 and 2
C1	20	160	20.0	2	1
C2	20	100	15.0	2	1
C3	20	200	15.0	2	2
C4	20	210	15.0	fluid	1 and 2
HU	220	220	-	2	
CU	10	10	-	2	

Annuity factor 0.192072 (-)
HEX cost for streams [€] = $8600 + 670 \cdot A^{0.83}$ (A in m^2)
Annual Hot Utility cost [$€/kW \cdot a$] = 100
Annual Cold Utility cost [$€/kW \cdot a$] = 10

3.1.2. Electricity price high and investment cost normal, (ElP=B,ANN=A)

When comparing the cases when electricity price is high and investment costs are normal (ElP=B,ANN=A), it is clear that

- Interplant heat exchanging is beneficial
- Only nanofluids TiO_2 0.6% and MgO 1.0% provide possibilities for small cost reductions compared to water
- MgO 1.0% is slightly the best fluid
- It is clear that the solution of TiO_2 0.6% is a bad local solution
- Integration in general and designing the heat exchanger network is much more important that finding the optimal heat transfer material

The best network for this case, which is MgO 1.0% , is presented in Figure 5. All networks are presented in the Supplementary material.

3.1.3. Electricity price normal and investment costs high, (ElP=A,ANN=B)

When comparing the cases when electricity price is high and investment costs are normal (ElP=B,ANN=A), it is clear that

- Interplant heat exchanging is beneficial
- All nanofluids provide possibilities for small to substantial cost reductions compared to water
- SiO_2 4.0% is clearly the best fluid
- Integration in general and designing the heat exchanger network is more important that finding the optimal heat transfer material, but in this case also choosing the correct nanofluid is very important

Table 8: Main results of Example

CASE	Description [-]	HU $[kW]$	CU $[kW]$	Area $[m^2]$	Units [-]	EL $[kW]$	Total cost $[\frac{ke}{a}]$
Reference	$ElP = A, ANN = A$	3450.0	600.0	326.4	8	275.4	389.0
Reference	$ElP = B, ANN = A$	3307.6	457.8	339.3	9	325.9	390.0
Reference	$ElP = A, ANN = B$	3327.3	477.3	406.7	9	333.5	421.2
Water	$ElP = A, ANN = A$	2850.0	0 .0	301.5	8	301.5	325.9
Water	$ElP = B, ANN = A$	2850.0	0.0	340.4	8	298.5	334.7
Water	$ElP = A, ANN = B$	2850.0	0.0	577.8	9	500.9	391.7
TiO_2 0.6%	$ElP = A, ANN = A$	2850.0	0.0	329.4	8	301.5	325.4
TiO_2 0.6%	$ElP = B, ANN = A$	3307.7	457.7	420.4	9	354.1	391.9
TiO_2 0.6%	$ElP = A, ANN = B$	2850.0	0.0	549.8	9	506.1	389.3
TiO_2 1.0%	$ElP = A, ANN = A$	2850.0	0.0	322.2	8	308.4	325.2
TiO_2 1.0%	$ElP = B, ANN = A$	2850.0	0.0	322.2	8	308.4	334.4
TiO_2 1.0%	$ElP = A, ANN = B$	2850.0	0.0	449.1	8	433.7	380
MgO 1.0%	$ElP = A, ANN = A$	2850.0	0.0	322.7	8	293.6	**324.9**
MgO 1.0%	$ElP = B, ANN = A$	2850.0	0.0	322.7	8	293.6	**333.6**
MgO 1.0%	$ElP = A, ANN = B$	2850.0	0.0	450.3	8	403.2	379.5
SiO_2 1.0%	$ElP = A, ANN = A$	2850.0	0.0	321.2	8	315.7	325.3
SiO_2 1.0%	$ElP = B, ANN = A$	2850.0	0.0	321.2	7	315.7	334.7
SiO_2 1.0%	$ElP = A, ANN = B$	2850.0	0.0	446.6	8	448.7	380.1
SiO_2 4.0%	$ElP = A, ANN = A$	2850.0	0.0	312.894	8	368.34	325.7
SiO_2 4.0%	$ElP = B, ANN = A$	2850.0	0.0	351.4	8	438.0	340.1
SiO_2 4.0%	$ElP = A, ANN = B$	2850.0	0.0	333.4	9	453.8	**369.3**

The best network for this case, which is SiO_2 4.0% , is presented in Figure 6. All networks are presented in the Supplementary material.

Regarding the results in general, MgO 1.0% has the biggest potential to act as an intermediate stream regarding total annual cost when the investment costs (cost of money) are not especially high to normal conditions. When the investment costs (cost of money) are high to normal conditions, SiO_2 4.0% is clearly the best choice. In this situation choosing the correct nanofluid becomes an important issue, but in other situations (money costs normal and electricity costs normal or high) the possibility to integrate process streams freely comes much more important. Interestingly the utility consumption is always the same in all cases when inter-plant heat exchanging is allowed except in one case where the solution was clearly a bad local solution. This might indicate that hot and cold utility prices should have been varied as well or a different example should have been used. Otherwise the model reacts logically: with increasing electricity prices the benefit of using nanofluids decreases and with increasing investment costs (money costs) the nanofluids become a clear possibility. It is also clear that an double increase in annuity factor effects more than a three-fold increase in electricity cost.

The networks of the best solutions are presented in most

3.2. Medium size example

Next the model is used to optimize a slightly larger example. The data of the example is given in Table 9, which also shows which streams are in which processes. The problem has five hot process streams and six cold process streams that are in three different processes. T_{mapp} for all heat exchangers is 1. Number of stages is equal to 2. The

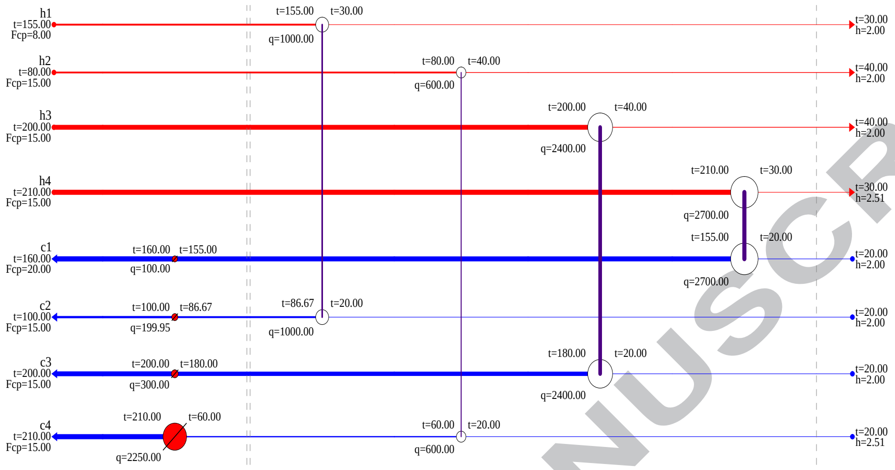

Figure 4: Small, MgO 1.0% , Ann=A, El=A.

model is solved with six different fluids and the electricity cost (108 and 36 $\frac{\text{€}}{kW}$) and the annuity factor are varied (0.192072 and $2 \cdot 0.192072$) for each fluid. Additionally there is a reference case, where no heat exchange between processes is allowed. Hot stream 5 and cold stream 6 are the intermediate streams that are allowed to transfer heat also between different processes. In the reference case both hot stream 5 and cold stream 6 belong to group 1. ELP=A stand for electricity cost 108$\frac{\text{€}}{kW}$ and ELP=B stands for electricity cost 36$\frac{\text{€}}{kW}$. ANN=A stands for annuity factor 0.192072 and ANN=B for annuity factor $2 \cdot 0.192072$.The problems are solved with GAMS (Brook et al., 2008). The MINLP solver used together with GAMS is DICOPT[4]. The NLP solver used in Dicopt is CONOPT3[5] and the MILP solver is CPLEX[6].

The main results of all cases are shown in Table 10.

3.2.1. Electricity price normal and investment cost normal, (ElP=A,ANN=A)

When comparing the cases when electricity price and investment costs are normal (ElP=A,ANN=A), it is clear that

- Inter-plant heat exchanging is beneficial
- All nanofluids provide possibilities for cost reductions compared to water, except SiO_2 4.0%
- MgO 1.0% is slightly the best fluid
- Integration in general and designing the heat exchanger network is, but not substantially, more important that finding the optimal heat transfer material

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[4] Engineering Design Research Center (EDRC) at Carnegie Mellon University

[5] ARKI Consulting and Development A/S

[6] ILOG CPLEX Division

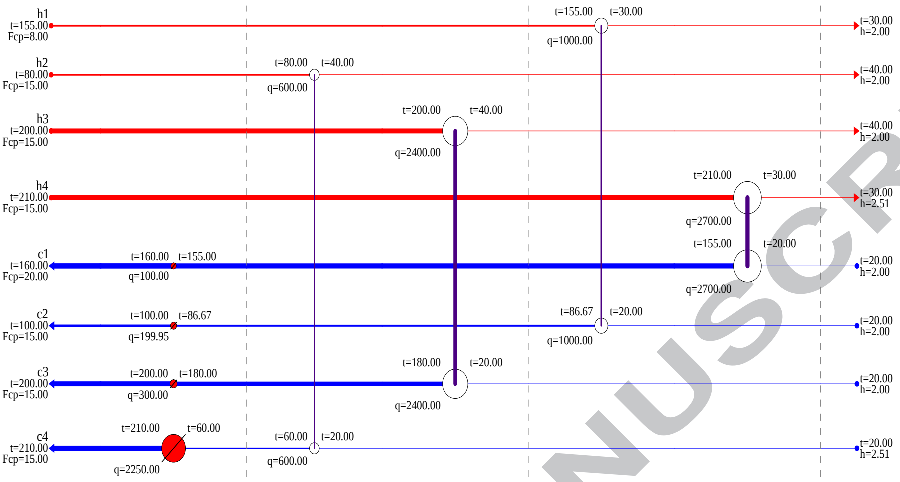

Figure 5: Small, MgO 1.0% , Ann=A, El=B.

The best network for this case, which is MgO 1.0% , is presented in Figure 7. All networks are presented in the Supplementary material.

3.2.2. Electricity price high and investment cost normal, (ElP=B,ANN=A)

When comparing the cases when electricity price is high and investment costs are normal (ElP=B,ANN=A), it is clear that

- Interestingly inter-plant heat exchanging was only slightly beneficial, when TiO_2 1.0% and MgO 1.0% are used, and even harmful else. This must be because only locally optimal solutions are provided, but also for the reason that in this problem and case, electricity costs seem to have such an big impact on the total annual costs
- All nanofluids provide possibilities for cost reductions compared to water when inter-plant heat exchanging is possible
- MgO 1.0% is slightly the best fluid

The best network for this case, which is MgO 1.0% , is presented in Figure 8. All networks are presented in the Supplementary material.

3.2.3. Electricity price normal and investment costs high, (ElP=A,ANN=B)

When comparing the cases when electricity price is high and investment costs are normal (ElP=B,ANN=A), it is clear that

- Interplant heat exchanging is very beneficial
- All nanofluids provide big possibilities to substantially reduce costs compared to water

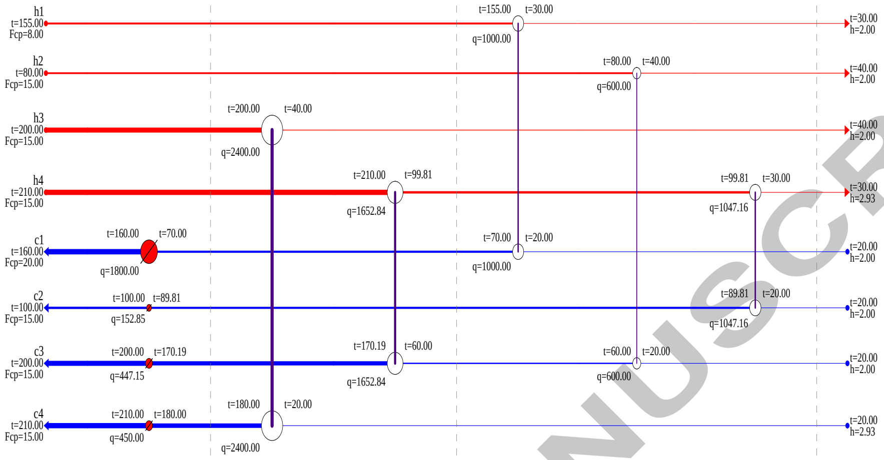

Figure 6: Small, SiO_2 4.0% , Ann=B, El=A.

- SiO_2 4.0% is clearly the best fluid, although TiO_2 1.0% and SiO_2 1.0% provide big cost reduction possibilities
- Integration in general and designing the heat exchanger network is very important in finding the optimal heat transfer material, but in this case also choosing the correct nanofluid is very important

The best network for this case, which is MgO 1.0% , is presented in Figure 9. All networks are presented in the Supplementary material.

Regarding the results in general, MgO 1.0% has the biggest potential to act as an intermediate stream regarding total annual cost in all cases. SiO_2 4.0% , which is the strongest nanofluid, outperformed water only when the investment costs (cost of money) was high. Interestingly when electricity costs are high, inter-plant heat exchanging might not be beneficial. This might be because there is enough intra-plant heat exchanging possibilities in this problem and when electricity costs are high, the focus goes into decreasing pumping costs. In general the model reacts logically: with increasing electricity prices the electricity consumption decreases and with increasing annuity factor investments decrease, although in this problem the three-fold electricity cost seems to be a more important factor that the two-fold increase in investment costs.

4. Conclusions

Inter-plant heat exchanging is a means to improve the energy efficiency of a system of different processes in a cost-efficient manner so that the inter-plant heat exchange can be prioritized. In this work the effect of using nanofluids in streams transferring heat from different processes by optimizing the total cost of a heat exchanger network is studied. A superstructure approach is used in the model where te objective is to minimize the total annual cost (energy and investments) of the network. In the model

Stream	TIN [$^\circ$C]	TOUT [$^\circ$C]	FCp [$\frac{kW}{^\circ C}$]	H [$\frac{kW}{m^2 \cdot ^\circ C}$]	Process
H1	200	120	300.0	1	1
H2	500	120	250.0	1	2
H3	120	119	15000.0	1	3
H4	200	30	200.0	1	3
H5	500	30	300.0	FLUID	ALL
C1	165	220	500.0	1	1
C2	139	500	150.0	1	2
C3	20	250	100.0	1	2
C4	110	160	250.0	1	3
C5	200	201	25000.0	1	3
C6	20	500	300.0	FLUID	ALL
HU	1000	550	-	0.1	
CU	5	6	-	1	

Annuity factor 0.192072 [-]
HEX cost for streams [€] $= 8600 + 670 \cdot A^{0.83}$ (A in m^2)
Annual Hot Utility cost [$€/kW \cdot a$] $= 100$
Annual Cold Utility cost [$€/kW \cdot a$] $= 10$

Table 9: Process data for medium size example.

used for this analysis heat can be transferred directly between process streams in the same process and using intermediate streams for heat transfer between different processes. The intermediate streams are process streams, but these are the only streams whose heat can be transferred to other processes. These intermediate streams are the ones were different fluids are tested.

The model has been used to solve two problems. Additionally some key parameters (electricity cost and annuity factor) are varied to analyze their effect on the solution. The results show that nanofluids, especially MgO 1.0% can improve total annual costs when used as intermediate streams, especially if electricity costs are small compared to other costs. With normal electricity prices and when investment cost (money costs) are normal, most, or even, all of the benefits of saving heat transfer area goes into increased pumping costs. But when electricity is cheap, nanofluids seem to provide cost savings. All together it is clear that the choice of an optimal nanofluid is case dependent. As a future work, it would be interesting to see are there any benefits to mix nano materials with special fluids intended for heat transfer and to optimize these mixtures for specific applications.

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Table 10: Main results of medium size example

CASE	Description [-]	HU $[kW]$	CU $[kW]$	Area $[m^2]$	Units [-]	EL $[kW]$	Total cost $[\frac{ke}{a}]$
Reference	$ElP = A, ANN = A$	113460.3	151310.3	14098.6	13	485436.9	19192.1
Reference	$ElP = B, ANN = A$	247150.0	285000.0	9943.7	11	434193.9	41318.1
Reference	$ElP = A, ANN = B$	94164.6	132014.6	34472.0	12	610184.7	20669.9
Water	$ElP = A, ANN = A$	83056.8	120906.8	13614.4	14	646707.6	17613.912
Water	$ElP = B, ANN = A$	207450.0	245300.0	10205.6	12	336071.8	42314.6
Water	$ElP = A, ANN = B$	86284.5	124134.5	12798.9	14	536681.7	18348.4
TiO_2 0.6%	$ElP = A, ANN = A$	74846.7	112696.7	13622.1	14	626502.5	16619.7
TiO_2 0.6%	$ElP = B, ANN = A$	207450.0	245300.0	9937.2	12	326635.7	41609.3
TiO_2 0.6%	$ElP = A, ANN = B$	51608.1	89458.1	12536.9	15	465844.9	14377.8
TiO_2 1.0%	$ElP = A, ANN = A$	74788.0	112638.0	13312.5	14	609242.7	16477.8
TiO_2 1.0%	$ElP = B, ANN = A$	20745.0	245300.0	9762.9	12	323599.3	41259.9
TiO_2 1.0%	$ElP = A, ANN = B$	45276.2	83126.2	12815.9	14	513810.4	13680.1
MgO 1.0%	$ElP = A, ANN = A$	74627.9	112477.9	13332.4	14	610797.1	**16343.1**
MgO 1.0%	$ElP = B, ANN = A$	207450.0	245300.0	9774.9	12	315151.4	**40967.9**
MgO 1.0%	$ElP = A, ANN = B$	40506.3	78356.3	11850.8	14	473613.7	**12875.7**
SiO_2 1.0%	$ElP = A, ANN = A$	82554.5	120404.5	12364.0	14	589744.0	17165.2
SiO_2 1.0%	$ElP = B, ANN = A$	207450.0	245300.0	9736.7	12	326960.7	41346.4
SiO_2 1.0%	$ElP = A, ANN = B$	40898.3	78748.3	11351.5	14	473561.0	13037.9
SiO_2 4.0%	$ElP = A, ANN = A$	128010.4	165860.4	10794.3	13	370198.3	21508.1
SiO_2 4.0%	$ElP = B, ANN = A$	207450.0	245300.0	9534.7	12	351494.9	41950.9
SiO_2 4.0%	$ElP = A, ANN = B$	58160.8	96010.8	9335.2	13	544077.7	14869.1

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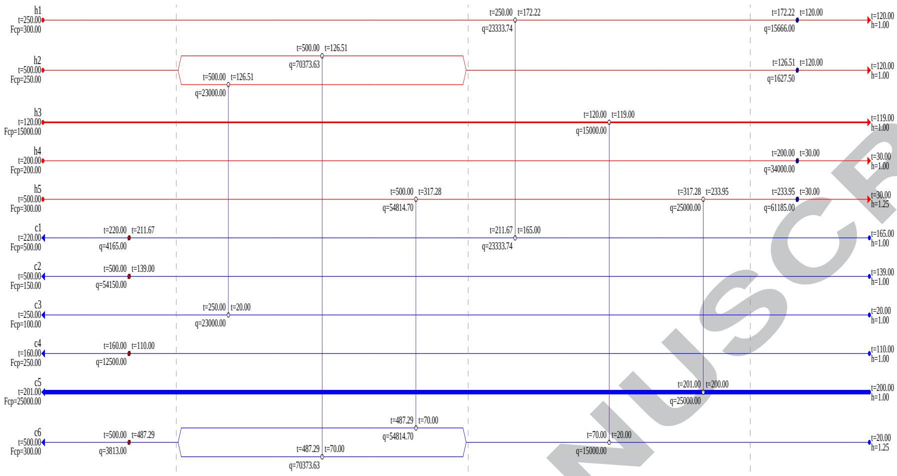

Figure 7: Medium, MgO 1.0% , Ann=A, El=A.

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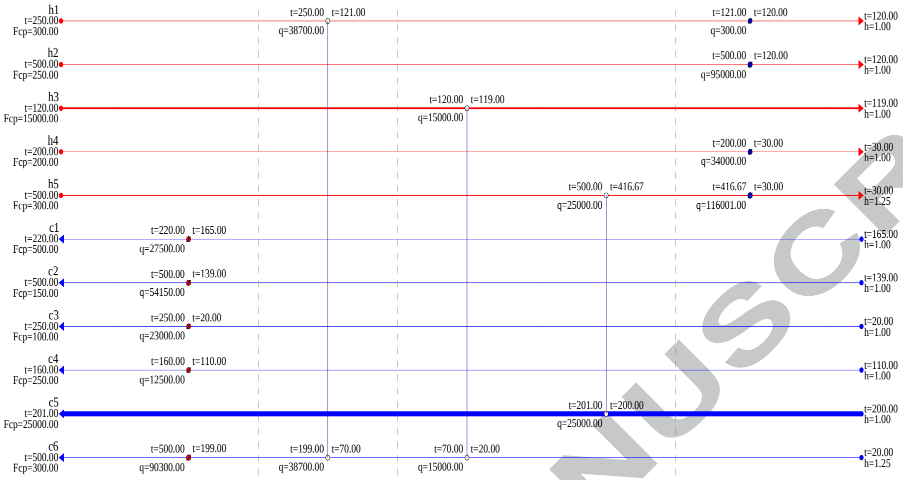

Figure 8: Medium, MgO 1.0% , Ann=A, El=B.

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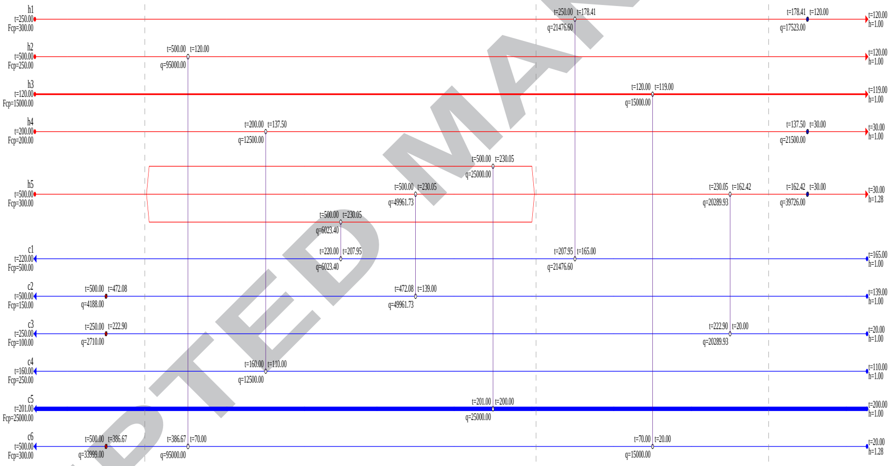

Figure 9: Medium, MgO 1.0% , Ann=B, El=A.

HIGHLIGHTS

Five nanofluids and water are used as intermediate streams in inter-plant heat exchange

If electricity price is low compared to other economic factors, using nanofluids can save costs substantially

Most of the improvement in heat transfer is balanced with increased pressure drop when using nanofluids

A mixture of water and 1% MgO performs best in most situations

Choosing a nanofluid for inter-plant heat exchanging is case-specific