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Numerical study of energy performance of nanofluids used in secondary loops of refrigeration systems

Fatou Toutie Ndoye[*], *Patrick Schalbart, Denis Leducq, Graciela Alvarez*

Irstea, Refrigeration Process Engineering Research Unit, 1 rue Pierre-Gilles de Gennes, 92761 Antony, France

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ABSTRACT

A mathematical model was developed in order to predict the energy performances of refrigerating systems using nanofluids for application in refrigeration plants of cold chain. The model was based on a combination of the Effectiveness-Number of Transfer Units method and classical heat transfer and fluid hydrodynamic correlations. The practical benefit of using nanofluids was evaluated through a global energy approach using the Performance Evaluation Criterion (PEC) which compared the heat flow rate transferred to the required pumping power in the refrigeration system. Simulations were done for a tubular heat exchanger in laminar and turbulent regimes, for various types of nanoparticles (Al_2O_3, Co, CuO, Fe, SiO_2 and TiO_2) and a wide range of volume fraction. It was shown that heat transfer coefficients significantly increased with the increase of nanoparticles concentration for laminar and turbulent flow regimes. However, the pressure drop which is directly related to the pumping power also increased with the increase of nanoparticles concentration whatever the flow regime. Calculation of PEC has shown that the energy performance is strongly dependent on the type of nanoparticles: some of the studied nanofluids (Al_2O_3, SiO_2, TiO_2) were clearly less efficient than the base fluid while the others (Co, CuO, Fe) had a favourable energy performance with PEC values reaching 80%. The model was validated using published data and it was shown that classical existing correlations success to represent heat transfer and pressure loss behaviours of nanofluids in heat exchangers, when the effective thermal and physical properties are taken into account. This study showed the great potential of nanofluids to improve cold chain efficiency by reducing energy consumption, emissions and global warming impact.

Etude numérique de la performance de nanofluides utilisés dans des boucles secondaires de systèmes frigorifiques

Mots clés : Nanofluides ; Chaîne du froid ; Réfrigération ; Performance énergétique

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[*] *Corresponding author*. Tel.: +33 1 40966161; fax: +33 1 40966475.
E-mail address: fatou-toutie.ndoye@irstea.fr (F.T. Ndoye).

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Nomenclature

Latin symbols

A	Internal heat exchange area, m^2
Cp	Specific heat, $J\ kg^{-1}\ K^{-1}$
C_r	Heat capacity ratio, –
d	Tube diameter, m
E	Heat transfer effectiveness, –
H	Relative viscosity, –
h	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
k	Thermal conductivity, $W\ m^{-1}\ K^{-1}$
L	Length, m
$\dot{m}$	Mass flow rate, $kg\ s^{-1}$
n	Shape factor, –
NTU	Number of Transfer Units, –
Nu	Nusselt number, –
PEC	Performance Evaluation Criterion, –
Pr	Prandtl number, –
Re	Reynolds number, –
R_w	Thermal resistance, $m^2\ K^{-1}\ W^{-1}$
S	Internal cross section area, m^2
T	Temperature, K
U	Overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
v	Velocity, $m\ s^{-1}$
$\dot{v}$	Volumetric flow rate, $m^3\ s^{-1}$

Greek symbols

ΔP	Pressure drop, Pa
Λ	Darcy coefficient, –
μ	Dynamic viscosity, Pa s
ρ	Density, $kg\ m^{-3}$
ϕ	Concentration, –
ψ	Sphericity, –

Subscripts

bf	Base fluid
c	Cool
h	Heat
i	Inlet; Inner
m	Mass
nf	Nanofluid
o	Outlet; Outer
p	Particle
v	Volume
w	Wall

1. Introduction

One of the major concerns of the cold chain sector is to improve the energy efficiency of refrigeration systems while reducing their environmental impact. Several researches have been conducted in the field of refrigeration technologies and various methods have been proposed in order to enhance heat transfer rate and diminish refrigerant charge. Secondary refrigeration architecture has been identified as a good strategy of reduction of refrigerant charge, but is thermally less efficient than traditional direct refrigeration systems (Macchi et al., 1999; Poggi et al., 2008; Wang et al., 2010). A way to overcome this issue could be the use of secondary fluid such as nanofluids with excellent heat transfer properties. Nanofluids have the potential to be applied in current secondary loop refrigeration systems throughout the cold chain (Kumaresan et al., 2013).

Nanofluids are a new class of solid–liquid composite materials consisting of solid nanoparticles (NPs), with typically sizes of 1–100 nm, suspended in a liquid carrier. Nanofluids recently gained worldwide attention in heat transfer field due to their higher thermal conductivity in comparison with conventional heat transfer fluids (e.g. water, ethylene glycol, etc). The increase in thermal conductivity because of very small sizes and large surface specific areas of NPs results in an enhancement of heat transfer properties. Choi and Eastman (1995) first proposed the use of NPs instead of millimetre and micrometre size particles to enhance thermal conductivity of fluids while avoiding clogging and stability problems. Therefore, researches about convective heat transfer in nanofluids have been increasing for various applications such as electronics, air conditioning and refrigeration. Recent studies have revealed that the enhancement of thermal conductivity is accompanied by an increase in viscosity leading to pressure drop and pumping power increase (Vajjha et al., 2010; Ferrouillat et al., 2011, 2013; Maré et al., 2011; Ferrouillat et al., 2013; Mahbubul et al., 2013a,b). Therefore, this poses the problem of finding a compromise between thermal transfer enhancements and pumping energy losses, before using NPs in heat exchangers.

For refrigeration applications, scientists usually investigated the use of NPs as additives with conventional refrigerants and oils in order to make refrigeration systems more efficient (Kim et al., 2007; Jung et al., 2011; Saidur et al., 2011; Yang et al., 2012; Mahbubul et al., 2013a,b). These works have demonstrated that such fluids, named nanorefrigerants, had the potential to enhance heat transfer rate thus reducing energy consumption. A few studies have focused on the use of nanofluids in heat exchangers for cooling applications. Maré et al. (2011) compared the thermal performances of two nanofluids used at temperature between 0 and 10 °C in a plate heat exchanger. They found that the convective heat transfer was improved and pointed out the importance to take into account the competition between thermal performance (heat transfer) and pumping power (pressure drop). Sarkar (2011) and Kumaresan et al. (2013) studied the use of nanofluids in a secondary loop for refrigeration. But these authors only evaluated the thermal performance of the system without considering pressure drop issues. Moreover, they worked at temperatures above 0 °C. So, to the best of authors' knowledge, there is no publication available that dealed with the use of nanofluids in a secondary loop of a refrigeration system for freezing and chilling applications and focussing on the comparison between heat transfer enhancement and pumping power loss.