Applied Thermal Engineering 30 (2010) 962–969

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Energetic performances of a refrigerating loop using ice slurry

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ARTICLE INFO

Article history:
Received 29 June 2009
Accepted 7 January 2010
Available online 11 January 2010

Keywords:
Secondary heat transfer fluid
Monophasic
Ice slurry
Pressure drop
Pumping power
Modelling

ABSTRACT

The consideration of environmental constraints in production, transport and distribution of cold energy resulted in reconsidering the practices of installations dimensioning in particular. Their containment led to the development of secondary refrigerants such as ice slurries to store, transport and distribute the cold energy. These heat transfer fluids should have good thermophysical properties, giving high transport capability, high heat transfer ability as well as low pressure drops. The use of ice slurries can lead to lower flow rates and smaller pumping power compared to single phase fluid. The purpose of the presented work is to study the distribution network of indirect cold systems thanks to a model allowing the evaluation of the influence of various parameters on the operating behaviour of the installation. The available domain for the use of secondary heat transfer fluid (whether in their single phase or two phase form) is determined considering the best design from an energetic point of view. Because of the essential role of the fluid distribution between the production site and consumers, we focus our study on pressure drops and pumping power due to the fluid flow in cooling loops. For each investigated case, the minimum consumption power is obtained with the two phases (solid–liquid) heat transfer fluid (ice slurry).

1. Introduction

During the last decade, some refrigerants have been identified as ozone depleting and/or greenhouse substances. So, industrial and commercial sectors have been working to find alternative refrigerants having both good physical and thermodynamic characteristics as well as less adverse effects on the environment. In the same time, work has been done to reduce the amount of refrigerant in installations by the use of secondary refrigeration loops. The heat transfer fluid in those loops is very often water or an aqueous solution. These systems usually use single phase heat transfer fluids but it is possible to improve their efficiencies by using diphasic secondary refrigerants such as ice slurries. Ice slurry is a mixture of an aqueous solution and fine ice crystals. This promising technology has main advantages in particular thanks to the latent heat of ice: a more efficient heat transfer fluid, better temperature stabilization and higher power [1].

These features have made ice slurries a competitive alternative to conventional secondary refrigeration systems [2]. For example, it has been successfully employed in many applications from comfort cooling and commercial refrigeration to industrial production processes [3]. However, more engineering information is required on fluid flow and heat transfer characteristics as well as on a reliable, energy efficient and cost effective production of the ice, for ice slurries to become more widely accepted.

The transport properties of ice slurry have been studied extensively. Most previous studies focussed on the heat transfer and pressure drops [4].

Niezgoda-Zelasko [5], Niezgoda-Zelasko and Zalewski [6] and recently, Grozdek et al., [7,8] present results of studies on pressure drops and heat transfers in ice slurry flows through horizontal tubes. The secondary fluid was prepared by mixing ethanol and water to obtain an initial alcohol concentration of about 10%. Generally, with higher ice mass fraction and velocity, they found that the heat transfer is enhanced and the pressure drop is high in comparison to the single phase flow. Up to ice mass fraction between 10% and 15% the mean heat transfer coefficient shows only slight (laminar regime) or no increase (turbulent regime) in comparison to single phase flow. Beyond that ice mass fraction, the heat transfer coefficient is increased significantly. The same evolution was found for pressure drops. However for ice concentrations of 15% and higher, certain velocity exists at which the ice slurry pressure drop is lower than for single phase flow (transition zone from turbulent to laminar).

Bédécarrats et al. [9] studied the behaviour in heat exchangers of ice slurry composed of fine ice particles inside an ethanol–water solution. The heat transfer and friction characteristics were studied in two double pipe heat exchangers, one with a smooth surface and another with an improved surface. Heat transfer coefficients and

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1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2010.01.006

Nomenclature

d	diameter, m
f	friction factor
h	specific enthalpy, J kg^{-1}
L	length, m
$\dot{m}$	mass flow rate, kg s^{-1}
T	temperature, K
ΔP	pressure drop, Pa
Re	Reynolds number
X	fraction
$\dot{Q}$	heat flux, W
V	velocity, m s^{-1}
$\dot{W}$	pumping power, kW

Greek letters

ρ	density, kg m^{-3}
η_{pump}	pump efficiency
μ	dynamic viscosity, Pa s

Subscripts

app	application
in,out	inlet, outlet
eq	equivalent
d	diphasic
f	fluid
is	ice slurry
ai	alcohol initial
nom	nominal
v	volumetric

pressure drops were experimentally investigated for the slurry flowing in the internal tube with ice mass fractions ranging from 0% to 30% and with flow velocities between 0.3 and 1.9 m s^{-1}. For some flow velocities, the results showed that an increase in the ice fractions caused a change in the slurry flow structure influencing the evolution of the pressure drops and of the heat transfer coefficients. Critical ice fraction values were determined corresponding to a change flow structure from laminar to turbulent motion revealed by the evolution of the friction factor.

However, very little work has been conducted on the flow of slurries through industrial heat exchangers. Norgaard et al. [10] studied the behaviour of ice slurry in a piping system, including pumps, plate heat exchangers and various types of fittings. They found that the pump performance decreases with increasing ice concentration due to the increasing viscosity of the ice slurry and the additional effect of the ice particles. For a standard plate heat exchanger, results indicated an increase in the overall heat transfer coefficient and pressure drop with increasing ice fraction. Pressure loss coefficients in selected fittings have been measured to reveal the dependency of ice concentration.

Jensen et al. [11] reported on heat transfer coefficients and pressure drops performed on three pipes measuring 12, 16 and 20 mm in diameter. The ice slurry mixture was based on 10% ethanol aqueous solution with an ice fraction of 0–0.30 and with a particle size of less than 0.2 mm. The velocity in the pipes was 0.5, 1.0 and 1.5 m s^{-1}. They report that the heat transfer coefficient increased with increasing ice fraction and velocity. For the hydraulic performance, they found no change in pressure drops with varying ice fraction as long as the ice fraction was lower than 0.1–0.15 and an increase beyond.

Bellas et al. [12] performed measurements on ice slurry (based on 5% propylene glycol aqueous solution) in a plate heat exchanger with an ice mass fraction between 0 and 0.25. The flow rate was between 1.0 and 3.7 m^3 h^{-1}. By increasing the ice mass fraction from 0 to 0.20 the pressure drop increased by around 15% over the flow range. The overall heat transfer coefficient of the plate heat exchanger increased significantly with increasing flow rate. The variation of ice fraction did not appear to have any effect on the overall heat transfer coefficient.

Shire et al. [13] conducted experiments to determine the characteristics of ice flows through industrial heat exchangers (plate heat exchanger and tubular heat exchanger) to extend the range of previous work to higher ice fractions. As expected from most previous research, the pressure drops experienced were greater than those with water, and rose with increasing ice fraction and flow rate.

The heat transfer and pressure drop results obtained by the different investigators indicate that the behaviour of ice slurries is a function of a number of parameters which include the mixture viscosity, the Reynolds number and the ice fraction. These parameters have an influence on the energy consumption in installation using secondary refrigeration loops.

There have few publications on the subject about the energetic advantages and the investments of installations using ice slurry. Haberschill et al. [14] have compared the use of ice slurry (water + ethanol) and chilled water in the case of air conditioning in a building. The result of this work is not favourable to ice slurry. This conclusion is explained by a high level of the temperature needed in the case of the air conditioning.

The main objective of our investigation is to verify the interest of the use of ice slurry for cooling systems.

Our goal in this work is to determine the available domain for the use of secondary heat transfer fluid (whether in their single phase or two phases form) and to find out the best design from an energetic point of view. Considering such an objective, researchers as well as engineers have to solve the problem consisting in distributing the maximum amount of heat with the lowest amount of energy needed to transport the fluid. As in other hydraulic energy transport systems, pumps are essential to distribute the fluid between the production site and consumers. So we will focus our study on pressure drops and pumping power due to the flow of a water/ethanol mixture in cooling loops.

Firstly, the studied installation and all considered assumptions of this investigation are described. Then, the used methodology is explained, in particular, to calculate the pressure drops (frictional losses in straight pipes and losses due to various fittings) created respectively in the two branches of the loop and in the industrial heat exchangers.

Finally, we present results obtained by the model developed in this work which enabled to evaluate the pumping power.

2. Model description

2.1. System description

As already mentioned we will focus our study on pressure drops and pumping power due to the fluid flow in cooling loops.

The investigated process that has been considered and that has been studied, has to exchange an amount of power $\dot{Q}_{app}$, at a fixed temperature T_{app} (Fig. 1). The secondary heat transfer fluid is