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Heat transfer and flow characteristics during the formation of TBAB hydrate slurry in a coil heat exchanger

*Hongxia Zhou *, Catalina Vasilescu, Carlos Infante Ferreira*

Delft University of Technology, Leeghwaterstraat 39, 2628 CB, Delft, The Netherlands

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ABSTRACT

The objective of this paper is to investigate the pressure drop and heat transfer characteristics of a coil heat exchanger in which TBAB hydrate slurry is being formed from a 36.5 wt % TBAB solution. The coil heat exchanger has a 5.6 mm internal diameter. First tests were carried out with water in order to validate the experimental method. TBAB hydrates are formed by cooling the mixture of TBAB and water at temperatures from 20 °C to 11 °C. Experimental heat transfer coefficients and pressure drop of TBAB hydrate slurry have been obtained with solid concentrations in the range of 10–45 wt %. The results are compared with values for TBAB solution and water. Existing pressure drop prediction methods can reasonably predict the experimental data. The experimental data cannot be predicted with existing heat transfer prediction methods. A method is proposed for the prediction of heat transfer under hydrate formation conditions.

Caractéristiques de transfert de chaleur et d'écoulement durant la formation de coulis d'hydrate de TBAB dans un échangeur de chaleur à serpentin

Mots clés : Coulis d'hydrate ; Échangeur de chaleur hélicoïdal à serpentin ; Transfert de chaleur ; Chute de pression ; Entreposage frigorifique

1. Introduction

The use of small primary refrigerant loops in combination with secondary-loop distribution of cold is considered a solution to overcome the problems associated with the use of toxic, flammable and even high GWP refrigerants which are reported, for instance, by Shi and Zhang (2013). In the secondary-loop distribution system, environment-friendly working fluids can be employed to store low temperature energy and to distribute

* *Corresponding author.* Delft University of Technology, Leeghwaterstraat 39, 2628 CB, Delft, The Netherlands. Tel.: +31 152789759.
E-mail address: h.zhou-1@tudelft.nl (H. Zhou).

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Nomenclature

A	area [m^2]
c_p	specific heat [J kg^{-1} K^{-1}]
d	diameter [m]
D_c	coil diameter [m]
De	Dean number [$\mathrm{Re}\sqrt{\frac{d}{D_c}}$]
f	friction factor
g	acceleration due to gravity [m s^{-2}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
H	height of coiled tubes
i	enthalpy [J kg^{-1}]
k	conductivity [W m^{-1} K^{-1}]
K	loss coefficient
K'	coefficient in Eq. (22)
L	length [m]
$\dot{m}$	mass flow [kg s^{-1}]
n	exponent in Eq. (22)
Nu	Nusselt number [$\frac{hd_i}{k}$]
p	pressure [Pa]
Pr	Prandtl number [$\frac{c_p\mu}{k}$]
$\dot{q}$	heat flux [J s^{-1}m^{-2}]
$\dot{Q}$	heat flow [J s^{-1}]
Ra_H	Rayleigh number [$g\beta\Delta TH^3\,\mathrm{Pr}\left(\frac{\mu}{\rho}\right)^{-2}$]
Re	Reynolds number [$\frac{\rho wd}{\mu}$]
Re_M	modified Reynolds number [$\frac{d^n w^{2-n}\rho_S}{8^{n-1}K'}$]
Ste	Stefan number [$\frac{c_{pS}\dot{q}d_i}{x\Delta i k_S}$]
T	temperature [K]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]
w	velocity [m s^{-1}]
x	solid mass fraction

Greek

Δ	difference
β	thermal expansion coefficient
δ	thickness [m]
μ	viscosity [Pa s]
ρ	density [kg m^{-3}]

Subscripts

b	thermostatic bath
c	coil
$crit$	transition
H	hydrate
i	inner
lat	latent heat
log	logarithmic
L	liquid
o	outer
p	particle
S	slurry
str	straight
w	wall

it to the different application sites. In this way the amount of primary refrigerant charged to the system is significantly reduced in comparison to conventional distributed direct expansion systems resulting in much smaller leakage risk. Also the primary refrigerant can be maintained in restricted spaces, again limiting the risk to the environment. Low temperature energy storage can be easily included in secondary-loop refrigeration and air-conditioning systems and is an effective method to shift peak electric load to off-peak time as part of the strategy for energy management in buildings. It also contributes to a reduction of installed power and allows for night time operation when lower heat rejection temperatures are available for the primary refrigeration cycle.

Water is mostly used as low temperature heat storage and distribution fluid. Since the use of water as storage medium leads to large storage volumes, ice and ice slurry have been presented as more compact storage alternatives. While in the water systems, only the sensible heat is used, whereas in ice and ice slurry systems, the latent heat is used, leading to much lower volumes. When ice is used the required evaporating temperature of the primary cycle can drop down to –12 °C leading to relatively large energy consumption when the application is air conditioning. Ice slurry is composed of water and ice particles, is pumpable and can be generated at higher evaporating temperature of the primary cycle. Evaporating temperatures of –5 °C are feasible so that the energy consumption is reduced in comparison to ice systems. The size of the storage tank and the pumping power is reduced in comparison to water because of the higher heat capacity of the slurry which includes the melting enthalpy of the ice crystals. Air conditioning systems are generally operated making use of chilled water that is heated from 7 to 12 °C. An aqueous solution of 36.5% tetra-n-butyl ammonium bromide $[CH_3(CH_2)_3]_4NBr$ (TBAB) undergoes a liquid/solid phase change at 12 °C making it very suitable to operate as a slurry in air conditioning systems. In this way aqueous TBAB hydrate slurries, which allow for evaporating temperatures of +5 °C, are very promising secondary-loop working fluids. They allow for latent low temperature heat storage at temperatures close to the application temperature (and so for reduced energy consumption), can operate at atmospheric pressure and require reduced storage and distribution line sizes. In this paper the heat transfer and pressure drop of these slurries are experimentally investigated and predicting methods are proposed. Douzet et al. (2013) have shown that an air-conditioning system can be established by replacing the standard refrigeration fluid by a slurry of TBAB hydrate crystals.

TBAB is a quaternary salt that crystallises in small solid particles, called hydrates, at operating conditions suitable for air conditioning applications (atmospheric pressure and temperatures in the range of 0–12 °C). TBAB hydrate slurry is a phase change material which is pumpable and can be used for cold storage purposes, can save energy and can reduce the peak electricity demand of air conditioning systems in the day time during summer. TBAB can form two types of hydrates with different hydration numbers. Type A has a columnar shape (Shimada et al., 2005) and a latent heat of 193 kJ kg^{-1}, while type B has an irregular form of thin crystals and has a latent