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Study of self-rewetting fluid applied to loop heat pipe

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ABSTRACT

This study investigated the application of self-rewetting fluid to loop heat pipe (LHP) and its effect on the heat transfer performance of LHP, proposing a most suitable solute and concentration for LHP. At a certain temperature, a self-rewetting fluid, contrary to common newtonian fluids, has the ability to reverse its surface tension's trend, inducing colder fluid to flow to the heated surface and delaying the occurrence of dry-out in LHP during operation. The most important variables for a self-rewetting fluid are its concentration and solute. Thus, this study focused on a few self-rewetting fluids (including butanol, pentanol, and hexanol aqueous solutions); the surface tensions of these fluids at different concentrations were measured to find the best self-rewetting fluid, and then it was applied to LHP as working fluid to investigate its effect on the heat transfer performance.

Results of surface tension measurement showed that, concerning the concentration of a self-rewetting fluid, the optimal concentration for a self-rewetting fluid was its saturation concentration; concerning the solute of a self-rewetting fluid, after comparing all the tested working fluids at the optimal concentration, 6% butanol aqueous solution was the best type of self-rewetting fluid. Results from applying 6% butanol to LHP as working fluid for performance testing showed that the critical heat load was 650 W and the total thermal resistance was 0.25 °C/W. Compared with LHP with regular working fluid, the critical heat load was 2.5 times higher and total thermal resistance decreased by about 60%, indicating high potential for self-rewetting fluids to enhance the heat transfer performance of LHPs.

1. Introduction

Loop heat pipe (LHP), proposed by Gerasimov and Maydanik in 1970, is a two-phase heat transfer device powered by the capillary force of its wick to pump the working fluid. Recently, with fast advancements in electronic devices, heat produced by electronic devices also increase rapidly; to meet the high heat transfer capacity requirements, two-phase heat transfer devices became the best candidates of choice. Loop heat pipes possess merits such as self-maintenance, high heat transfer capacities, and long heat transfer distances, displaying great potential as cooling devices for electronic products.

A loop heat pipe has five main components: evaporator, vapor line, condenser, liquid line, and compensation chamber. The wick in the evaporator is the most critical element; it provides capillary forces to pump the working fluid as well as blocks and prevents vapor from traveling back into the compensation chamber. Thus, the choice of LHP's working fluid is also important, as it must be able to work well with the wick and aide the evaporation process on the wick's surface. To enhance the LHP's heat transfer performance, one of the ways is to delay the occurrence of dry-out. Therefore, this study increased the wick's wettability by altering the LHP's working fluid, thereby delaying the occurrence of dry-out and increasing the LHP's critical heat load.

In 1973, Vochten [1] measured the surface tensions of high-carbon (at least four) alcohol aqueous solutions, finding that, contrary to pure substances, there is a non-linear relationship between the surface tensions of these fluids and temperature; instead of lower surface tension with higher temperature, at a certain temperature, an alcohol aqueous solution's surface tension starts increasing with increasing temperature. Since these types of alcohol aqueous solutions increase the wettability of higher-temperature surfaces, preventing the surfaces from drying, they were given the term" self-rewetting fluids." In 1999, Ahmed [2] pointed out that a very strong Marangoni effect due to

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Nomenclature

c	concentration (%)
D_i	inner diameter of the wick (m)
D_o	outer diameter of the wick (m)
K_w	permeability of the wick (m^2)
L_w	length of the wick (m)
$\dot{m}$	flow rate (kg/s)
P	pressure (N/m^2)
ΔP	pressure drop (N/m^2)
$\dot{Q}_{app}$	applied heat load to the evaporator (W)
r_c	effective pore radius of the wick (μm)
R_{total}	total thermal resistance of the system (° C/W)
$T_{c,in}$	heat sink temperature (°C)
$T_{c,out}$	condenser outlet temperature (°C)
T_{evap}	evaporator wall temperature (°C)
T_v	evaporator outlet temperature (°C)
V_{pore}	volume of pores in the wick (m^3)
V_{total}	volume of the entire wick (m^3)
x	x-axis
ε	porosity of the wick (%)
θ	contact angle (°)
ρ	density of fluid (kg/m^3)
σ	surface tension (mN/m)
σ_T	surface tension factor for temperature changes (mN/m-°C)
σ_c	surface tension factor for concentration changes (mN/m)
μ	viscosity (kg/m s)

concentration gradient was expected in dilute aqueous solutions of 2-propanol; they reported the CHF of 1.5 mol% of 2-propanol aqueous solution can be at least twice of that of water and also has a considerably higher nucleate boiling heat transfer coefficient. In 2001, Zhang [3] said that decreasing surface tension of the working fluid with increasing temperature is detrimental to the wettability of the heated surface, thus suggesting the use of self-rewetting fluids, whose surface tensions increase with increasing temperature.

From 2004 to 2007, Abe [4–7] performed a series of studies and showed that the Marangoni effect is caused by the combined effects of the surface tension gradient due to temperature differences and concentration gradient. The fluid would flow to a higher surface tension region due to the flow motion affected by the surface tension gradient, which causes the Marangoni flow. By inducing the liquid-phase working fluid to flow from lower-temperature region to higher-temperature region, the wettability of the surface can be increased, thereby delaying occurrence of dry-out, decreasing the operating temperature, and increasing the heat transfer performance.

In addition, from 2007 to 2010, Savino [8–10] made a series of reports concerning the application of self-rewetting fluids to heat pipes. Eq. (1) shows that the self-rewetting fluid's concentration and temperature are important indexes for its surface tension; results from experiments also showed that self-rewetting fluids effectively enhanced the heat transfer performance compared to water, lowering the overall operating temperature.

$$\frac{\partial \sigma}{\partial x} = \sigma_T \frac{\partial T}{\partial x} + \sigma_c \frac{\partial c}{\partial x} \tag{1}$$

In 2008, Francescantonio [11] applied heptanol aqueous solution to heat pipe and found that, compared to using pure water, the critical heat load was increased by a factor of two and the total thermal resistance significantly decreased; the study further suggested that, with the proper choice of binary mixture, the performance of the heat pipe can be further enhanced. In 2009, Abe [12] applied, separately, butanol, pentanol, heptanol, and propanol aqueous solutions to heat pipe performance tests; results showed that butanol aqueous solution yielded the best results. In 2009 and 2010, Fumoto [13–15] applied butanol and pentanol aqueous solutions to heat pipe to investigate the effects of different working fluid filling ratios on the heat transfer performance, yielding clear enhancements to heat pipe's performance.

In 2001, Morovati [16] used butanol aqueous solution as working fluid at different concentrations to investigate the pool boiling heat transfer phenomenon under different pressures; the critical heat flux enhanced varied from 20% increase to 270% increase, and the vapor sizes produced during boiling were much smaller in butanol aqueous solution than in pure water.

Summing up the above literature survey, self-rewetting fluids can increase the critical heat flux during pool boiling heat transfer. Self-rewetting fluids, when applied to traditional wick-less heat pipes, can also lower the operating temperature and enhance the heat transfer performance; however, to-date reports on self-rewetting fluids applied to LHPs have yet to be seen, and detailed information concerning the concentrations and solute of the self-rewetting binary mixtures still need to be further verified. Therefore, this study investigated different self-rewetting fluids including butanol, pentanol, and hexanol aqueous solutions at different concentrations; the best self-rewetting fluid was determined from surface tension measurements and applied to LHP for heat transfer performance testing.

2. Materials and methods

2.1. Working fluid choices

The choice of working fluid is an important factor in the heat transfer performance of the LHP. This study focused on self-rewetting fluids; both the concentrations and solutes of self-rewetting fluids were investigated. The different solutes in this study were butanol, pentanol, and hexanol.

2.1.1. Different concentrations

Since the surface tension curves as functions of temperature for alcohol aqueous solutions vary for different concentrations, changing the concentrations of alcohol aqueous solutions can have significant impact on the surface tensions. In addition, as suggested by literature [12], the best concentration should be around the saturation concentration; under standard conditions, the saturation concentrations for butanol, pentanol, and hexanol aqueous solutions are 6%, 2%, and 0.6%, respectively. Therefore, in this study, the following concentrations were chosen for surface tension measurements to find the best concentrations: 2%, 4%, 6%, and 8% for butanol aqueous solutions; 1%, 2%, 3% for pentanol aqueous solutions, and 0.3%, 0.6%, and 0.9% for hexanol aqueous solutions.