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Research paper

Performance of compressed nickel foam wicks for flat vertical heat pipes

Geir Hansen*, Erling Næss

Department of Energy and Process Engineering, Norwegian University of Science and Technology, Kolbjørn Hejes vei 1a, 7491 Trondheim, Norway

HIGHLIGHTS

- Wicks for flat vertical heat pipes were produced from compressed nickel foam.
- Wicks of different degrees of compression were produced.
- Effective pore radius and permeability were determined by rate-of-rise using heptane.
- Porosity was determined using isopropanol.
- Wick performance was estimated for potassium as working fluid.

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ABSTRACT

The fabrication and performance of wicks for vertical flat heat pipe applications produced by compression of nickel foams has been investigated. The permeabilities and the effective pore radii for the wicks were estimated from rate-of-rise experiments, using the model fluid heptane. The porosities of the wicks were measured using isopropanol. The results, which are new and of vital importance for optimum use of such wicks, show that the permeabilities and the effective pore radii are in the upper range for heat pipe use. The joining pressure required during the sintering of the wicks was determined, and it was discovered that the nickel foams turned hydrophilic during the sintering.

1. Introduction

Well designed heat pipes have the ability to transport heat at high rates and at minimal temperature drop. The main reason for their high effectiveness is that the heat internally in the heat pipe is transported by vapour, utilizing evaporation and condensation of a working fluid. Heat pipes are in use in many fields and at many temperature levels, from cryogenic applications to the high temperatures in the metallurgical industries [1,2]. The number of available working fluids, especially for operation in the extreme temperatures, is limited. The same is true for the number of compatible construction materials and wicks. Inside the heat pipe the condensate is transported to, and distributed over the evaporator section by capillary forces created by a porous wick structure. The most attractive wick provides a high capillary pressure and at the same time an acceptable flow resistance. The heat pipe for a specific application is unfortunately often selected from a quite limited selection of heat pipe container materials, wick materials and structures, and working fluids. This is especially true for heat pipes needed for the extreme working temperatures. The current study was undertaken to provide wick design data for the wick of a vertical flat hybrid heat pipe/thermosyphon with potassium as working fluid, for operation up to 650 °C in the metallurgical industry. Model fluids (heptane and isopropanol) were used to characterize the wicks, as the characterization experiments would be very difficult to carry out with potassium due to its reactivity with air and moisture. Overviews over established materials, structures and working fluids suitable for different working temperatures are available in textbooks [1–4]. Recently Dillig et al. [5] carried out experiments with planar heat pipes using sodium as working fluid and different types of wick structures (screen mesh, sintered plates and grooves). The capillary limitation was identified as one of the main challenges in their study, underlining the importance of the wick structure optimization.

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* Corresponding author. Tel.: +47 73593938; fax: +47 73593580.
E-mail address: g.hansen@ntnu.no (G. Hansen).

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Nomenclature

Symbols

A_c	wick cross sectional area, m^2
g	gravity constant = 9.81 m/s^2
H	height, m
h_{fg}	latent heat of evaporation, J/kg
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
$\dot{Q}$	heat flow rate, W
r	radius, m
r_{eff}	effective pore radius, m
t	time, s
T	temperature
V	volume, m^3
W	width, m
y	height, m

Greek symbols

ε	porosity, –
θ	solid–liquid–vapour contact angle, degrees (°)
κ	permeability, m^2
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
σ	surface tension, N/m
δ	thickness, m
Δ	difference

Subscripts

cap	capillary
eff	effective (pore radius)
evap	evaporation
fric	friction
g	gravity
hs	hydrostatic
l	liquid
v	vapour
0	uncompressed

Wick optimization and development are also given much attention by researchers working on lower temperature systems, particularly wicks of grooves and/or sintered powders for loop heat pipe applications in the computer industry [6]. Usually the goal is to achieve high capillary pressure and high permeability, but the weight of the wick structure can also be a parameter for optimization [7]. For conventional single phase cooling systems various methods of surface optimization exist [8,9], however, the present paper deals with experimentally obtained characteristics of compressed nickel foam which may in the future lend itself to similar optimization.

Wick technologies can be combined. Recently Li et al. [10] analysed the performance of a cylindrical heat pipe with a composite wick having high permeability axial grooves which were covered (but not filled) by a layer of sintered copper powder. The performance was compared to the performance of a heat pipe with larger grooves filled with copper powder. The heat pipe with the active grooves had lower total thermal resistance, but the same maximum heat transfer rate as the heat pipe without active grooves. Jiang et al. [11] successfully developed and tested a novel porous crack composite wick for microchip cooling for working temperatures below 60 °C. Solomon et al. [12] used nanoparticles of copper to coat screen type wicks, and found that this reduced the thermal resistance in the evaporator of the heat pipe but increased the resistance of the condenser. The overall result was positive, since the total resistance was reduced.

Compression of nickel foam, as described by Sheehan et al. [13] and Queheillalt et al. [14], is one method of producing wicks which has so far not been given much attention. The method is particularly interesting because the degree of compression, and thereby the pore size and the wick properties can be tailored to best fit the requirement of the application at hand. Recently Silk and Myre [15] used compression to obtain the desired pore size for a carbon wick structure, for loop heat pipes using water as working fluid. Several layers of compressed foam can be sintered together to increase the total capacity of the wick. Huang, Franchi and Cai [16] created bimodal nickel wicks for heat pipes by sintering filamentary nickel powder onto uncompressed nickel foam. In the future even more tailor made wicks are anticipated, e.g. by sintering nickel powder onto compressed nickel foam.

Nickel foam was chosen as wick material by Queheillalt et al. [14] because it was considered compatible for a heat pipe using water as working fluid. Material compatibility makes nickel equally relevant for high temperature heat pipes using alkali metals such as potassium or sodium as working fluids. Stainless steel 304 is also compatible with potassium and sodium [1], but has a much lower thermal conductivity than nickel. Nickel foams are currently produced for the battery industry in large batches according to customer specifications. Unmodified foams usually have pore sizes of a few hundred microns, which are too large for heat pipe wick applications. The foams are usually characterized by the density, pore size and thickness. For heat pipe wick applications additional data are needed, especially related to the wettability and the flow characteristics of different wick and working fluid combinations. The key parameters for the flow characteristics are the permeability and the effective pore radius of the wick. The effective pore radius depends on the wettability, commonly described by the contact angle [17]. The porosity of the wick is another important parameter which is required in design processes, for instance in order to precisely calculate the amount of working fluid required in the heat pipe. In the present work the following elements have been investigated for the compressed nickel foam wicks:

- The wettability with water before and after the oxide reduction process.
- The joining pressure required on the layers during the sintering to achieve a mechanically strong multilayer wick.
- Porosities at different wick compression.
- Contact angles with heptane, estimated from measurements of maximum capillary rise and evaporation rates from the wicks.
- Effective pore radius and permeability estimates from rate-of-rise experiments with heptane.
- The effect of heptane evaporation and experiment duration on the rate-of-rise experiment results.
- The heat transfer capacity with potassium as working fluid.

2. Theory

In most heat pipe design calculations the wick is characterized by its porosity, permeability and effective pore radius. The theories behind the experimental determination of these parameters are based on assumptions which are mentioned in conjunction with the specific equations, however two recurring assumptions are: