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Incorporation of manufacturing constraints into an algorithm for the determination of maximum heat transport capacity of extruded axially grooved heat pipes

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ABSTRACT

In this study, an algorithm is proposed which takes into account the manufacturing (EDM and extrusion) constraints as well as container design, temperature drop criterion between the evaporator and condenser together the with the vapor and liquid pressure losses for axially grooved heat pipes. The algorithm was executed for rectangular, triangular, trapezoidal and reentrant grooved heat pipes for a fixed outer diameter with and without manufacturing constraints. It was seen that for all groove types, the maximum heat transport capacity was found to be higher for the case in which manufacturing constraints are neglected. Results also show that for trapezoidal and reentrant grooves, the width and depth combinations yielding the maximum heat transport cannot be actually manufactured. On the other hand, the maximum heat transport occurs in the range where the heat pipe can actually be manufactured for rectangular and triangular grooves.

1. Introduction

From Fourier's law of heat conduction perspective, heat pipes (HP) are accepted as extra-high thermal conductivity devices having the capability of transporting large amounts of heat between two terminals (evaporator and condenser) even in the presence of small temperature differences. This makes them to suitable for thermal control in both terrestrial and celestial applications.

HPs consists of three elements; container, working fluid and wick structure. Among different types of wick structures (groove, sintered and mesh) characterizing the heat pipes, grooved heat pipes are favored when the transportation of heat along relatively large distances is point of interest. Although this type of groove produces low capillary pumping (typically less than 100 Pa), flow resistance is so low (due to relatively big pore sizes) that the heat transport capacity turns out to be superior.

Although some complex steady state thermal mathematical models have been developed [1,2], reduced 1-D HP models [3–18] are continued to be used in computer codes for the design of heat pipes. When these codes are examined, it can be seen that the prediction of the heat transport performance is based on hydrodynamic losses due to friction in liquid, vapor flows and due to the liquid/vapor shear interaction. ANLHTP [11] is one of the earliest of these computer codes for the simulation of operation of heat pipes which is developed by Argonne National Laboratory. The code predicts heat pipe performance and temperature distribution during the steady-state operation. Later, Kamotani [12] developed a thermal analysis program for axially grooved heat pipes (HTGAP). The program can be used to predict both evaporator and condenser film coefficients for a specified groove geometry and operating conditions. GAP computer program [13] was designed on the other hand, to predict the steady-state heat transport capability of an axially grooved heat pipe for a specified groove geometry and working fluid. The capillary limit was determined by the numerical solution of the differential equation for momentum conservation with the appropriate boundary conditions. It also calculates the minimum required heat pipe wall thickness for pressure containment at design temperatures.

In addition to above, there are also studies on the geometrical optimization of characteristic lengths such as groove width, depth etc. In one of these studies, Do et al. [4] only considered the heat transport capability while optimizing width and depth of a rectangular grooved copper/water HP. The results showed that the optimum groove depth to width ratio should be around 3.65 at the working temperature of 90 °C. Kim et al. [7] proposed a model for the thermal optimization of a HP

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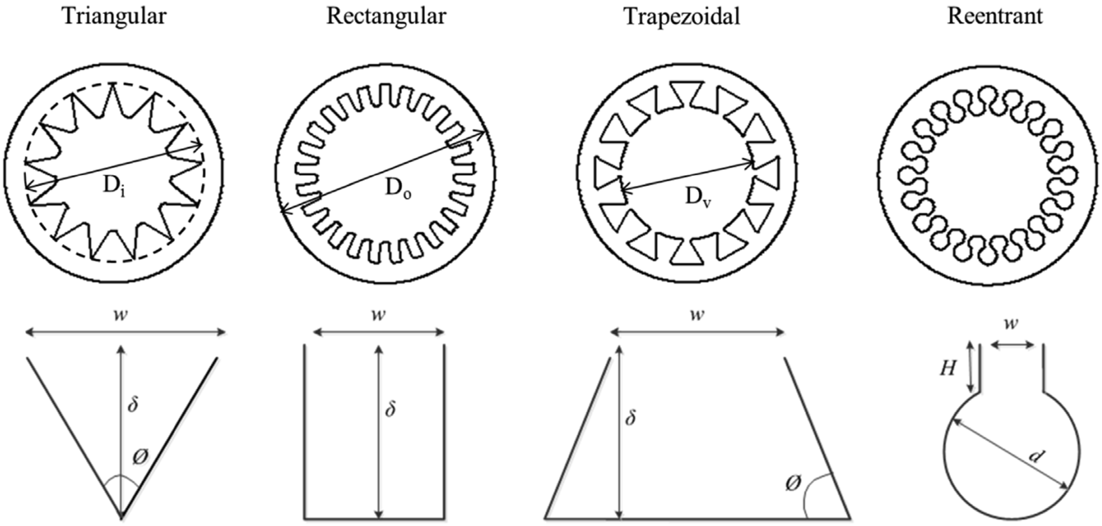

Fig. 1. Different types of groove geometries and their characteristic dimensions.

with trapezoidal grooves with respect to the width and the groove depth. However, their approach did not take into account the manufacturing constraints and does not include optimization of wall thickness, groove fin thickness, groove number which has significant effect on heat transport performance. Similarly, Chen et al. [14] developed a thermal model to predict the heat transfer capacity and the total thermal resistance for the heat pipe with trapezoidal grooves. It was shown that the groove wick structure with a wider groove base and higher groove depth could enhance the heat transport capability. However, the manufacturability of the HP remained still uninvestigated. Unlike these studies, Zhang et al. [15] studied a model for the investigation of the effect of the structural parameters on HPs with reentrant grooves. The model was used for the optimization of the heat transport capability and total thermal resistance. In this model, groove parameters (width, diameter, slot height), vapor core diameter and number of grooves were selected as optimization parameters. However, this is not holistic approach since a complete optimization process should have been based on the outer diameter (i.e. allowable space) of the HP while taking into account container thickness and manufacturing constraints.

Despite the fact that obtainable heat transport capacity of axially grooved HPs is mainly dictated by the fabrication stages, it was addressed in a very limited number of studies [5,17,19,20] until now. Extrusion is the process employed for the fabrication of axially grooved HPs from aluminum alloys which is used as container material for space applications due to its light-weight, high strength and thermal conductivity. Edelstein and Kosson [20] investigated the heat transport performance of a HP with reentrant grooves and stated that the groove geometry features (such as the number of grooves, groove diameter, groove opening, pipe diameter and wall thickness) should be adjusted with respect to manufacturing constraints in order to have better performance. However, his outcomes were only at recommendation level without describing a methodology. On the other hand, Brennan and Kroliczek [17] stated that the extrusion process sets the limits of the parameters such as the groove width and depth and the maximum groove depth should be limited to twice the groove width for a successful manufacturing. Recently, Ömür et al. [5] investigated the effect of extrusion limitations on heat pipe design and reported that extrusion limitations should be incorporated into the design phase. They have shown that heat pipes having groove depth to width ratios of 5 can still be manufactured and transport maximum heat. However, extrusion constraint alone is still not sufficient for governing all the manufacturing phases. Electro-discharge Machining (EDM) is a critical precursor of the manufacturing phase which is utilized in the production of the dies to be used in the extrusion process. EDM determines the maximum groove number that can be manufactured in a given heat pipe diameter and its effect was not studied until now.

In this study, an algorithm is proposed which takes into account the manufacturing limits (extrusion and EDM constraints) as well as container design, temperature drop criterion between the evaporator and condenser together the with the vapor and liquid pressure losses for axially grooved heat pipes. The algorithm was executed with and without manufacturing constraints in order to demonstrate their significance on the predictions. By extending the computations for different set of groove parameters, the range of groove shapes that are fictitious (cannot be manufactured) and the ones that can actually be manufactured were identified. To the authors' knowledge, a study which investigates the effect of extrusion and EDM limitations on the computation of maximum heat transport capacity for axially grooved heat pipes is not available in the literature.

2. Mathematical modelling

The global mathematical model developed in this study is based on the computation of maximum heat transfer capability by taking into account limitations due to

i. Capillary pumping and temperature drop between evaporator and condenser (thermal mathematical model)
ii. Manufacturing constraints
iii. Container design constraints

2.1. Capillary limit and temperature drop between evaporator and condenser: thermal mathematical model

The most widely used axially groove geometries found in HPs are shown in Fig. 1, where D_o is the outer diameter of a HP, D_i is the internal diameter (D_o minus container wall thicknesses), D_v is the vapor core diameter where only vapor flow (D_i minus groove depths), w is the groove width and δ is the groove depth. For the trapezoidal and triangular grooves, Ø represents groove angle whereas for the re-entrant groove type, d and H represent the groove radius and slot height respectively (see Fig. 1).

The maximum heat transport capacity of a HP is governed by five different limits [18]: the sonic limit, the entrainment limit, the boiling limit, the viscous limit, and the capillary limit. If the length of HP is sufficiently long, the capillary limit which is the lowest limit among these determines the maximum heat transport (for very short heat