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Analytical expression for thermal conductivity of heat pipe

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ABSTRACT

An analytical expression is proposed to predict the thermal conductivity of a heat pipe based on the heat transport limit equations. The experimental results of thermal conductivity of heat pipe measured at different heat inputs are compared with the thermal conductivity obtained from the analytical expression and found to be reasonable in agreement. The thermal conductivity of heat pipe obtained from the heat transport limit equation is also compared with lumped thermal resistant network model. The proposed analytical model is computationally effective and simple, and can be applied to a variety of applications. It is also useful for design and computational analysis of embedded heat pipes for machining applications.

1. Introduction

Metal machining is the most important form of metal removal process in industries such as automotive, aerospace, mold and die, consumer products, etc. During the metal machining process, a large amount of heat is generated due to the plastic deformation of material at the tool – work interface [1]. Heat generation is also found considerable even with the machining of metal matrix composites due to their abrasive nature [1–3]. Though a substantial portion of the heat generated during machining is carried away by the chip, continuous removal of metal by the machine tool increases the temperature of the cutting tool, work piece and machine.

Removal of heat generated in metal cutting operations is one of the most critical issues focused by the industries as increase in temperature above the permitted range will be detrimental to product dimensional accuracy, surface finish, tool wear and performance of the machine tool. In a typical machining process, a flood of coolant fluid is applied over the tool – work interface to carry away the heat. The contentious effects of coolant applied to remove heat during machining are widely reported in literature [4,5]. The toxic additives added to the coolant to improve its performance during metal cutting makes disposal of the coolant costly as it pollutes the environment. Dry machining and near dry machining have been developed [5] as other options to conventional machining however, are practiced limitedly. Recently, the applications of heat pipe to remove heat from turning tools, milling cutters [6–10], and drilling tools [11,12] are reported and look promising.

Heat pipes are passive heat transfer devices that can successfully transfer large amounts of heat. The robust and simple tubular structure with no moving parts makes the heat pipe a perfect choice to embed with rotating milling cutters. Recently, experimental [6–8,11,13] and numerical [6,7,11,14,15] studies are carried out to analyze the performance of heat pipe embedded in cutting tools. Zho et al. [14] performed an experimental study to analyze the feasibility and efficiency of heat pipe embedded drills by placing a heat pipe in the center of the drill with an evaporator positioned near the tip of the tool. A significant reduction in tool temperature is reported with the use of heat pipe embedded tools. It is also noticed that the prediction of maximum temperature in the tool along the rake face is an important parameter because of its influence on the tool life and quality of the machined part [2]. Numerical studies have gained more importance since measuring temperatures of the rotating cutting tool [16] is difficult [6,7]. However, these studies are complicated due to the non-linearity present in the equations governing vapor and liquid flow in a heat pipe. Shukla et al. [17] introduced an analytical model to determine the heat transport limit of a micro heat pipe considering capillary limit. Though several assumptions such as treating heat pipe as a material with high thermal conductivity [7,11], constant temperature cylinder [15], ignoring the phase change mechanism [18] etc., simplified the numerical solution, a more focused approach is required for the improvement of results. Hence, the approach of analytically modeling the thermal conductivity of a heat pipe is timely essential to find the temperature of the tool and is the focus in this study.

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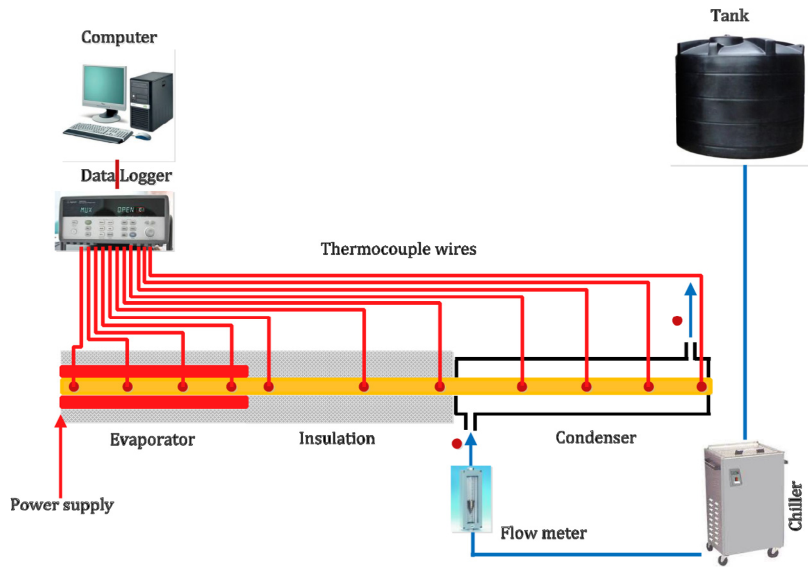

Fig. 1. View of experimental set up.

Thermal conductivity is an important parameter to determine the temperature variation between the evaporator and condenser sections of a heat pipe. In this direction, no report is available in the open literatures to the best of authors' knowledge. In the model proposed, the heat transport capacity of the heat pipe is assumed equal to the heat conducted by the heat pipe. Heat transport capacity of the heat pipe is estimated by comparing the capillary pressure generated by the wick structure and pressure losses that occur during vapor and liquid flow through the wick structure. Thermal conductivity of the heat pipe estimated by using Fourier law of heat conduction and lumped thermal resistance network model are compared with experimental measurements. Development of such analytical models will enable saving of a significant amount of experimental effort, computational cost and time.

2. Experimental methods

The proposed experimental test set up comprises of a test section, chiller and data acquisition system (Fig. 1). A straight copper tube of outer diameter 19 mm and length 350 mm forms the test section of the heat pipe. The corresponding lengths of the evaporator, adiabatic and condenser sections are 100, 100 and 150 mm, respectively. Four layers of copper screen mesh of wire diameter 80 µm and porosity 0.63 is used to fabricate a wick structure of thickness 1 mm. The wick structure is fixed to the inner wall of heat pipe by a spring support. The heat pipe is charged with 12 ml of DI water (deionized water), which is sufficient to saturate the complete wick structure.

The experimental setup consists of an electrical resistant heater having a maximum power input of 800 W to supply heat to the evaporator section. T-type (OMEGA) thermocouples with an uncertainty of ±0.2 °C are used to measure the wall temperatures of the heat pipe and the thermocouples are welded on the wall of heat pipe in the positions as shown in Fig. 2. Further, a thin layer of thermal interface material (TIM) is applied to minimize the heat resistance between surfaces of heater and evaporator sections of the heat pipe. A 40 mm thick glass wool with the thermal conductivity of 0.04 W/m-K is wound around the heater to reduce heat loss to the surroundings.

The condenser sector of the heat pipe is made of acrylic tube. Water from the reservoir is passed through the chiller and is supplied to the cooling jacket at a flow rate of 350 ml/min. The flow rate of the coolant is controlled using a calibrated flow meter having an uncertainty of ±3%. The temperature of the coolant is maintained at 22 ± 0.5 °C and the inlet and outlet cooling water temperature are measured using two OMEGA T-type thermocouples with uncertainty of ±2 °C. The entire experimental setup is placed horizontally with the help of a level indicator. Tests are carried out with heat inputs at the evaporator varying between 50 and 300 W. The heat pipe is allowed to reach a steady state and the temperature data are recorded over a time interval of 30 s.

The heat transported by the heat pipe under different heat loads is calculated by Newton law of cooling: $Q_t = \dot{m} \times C_p \times \Delta T$, where, $\dot{m}$ is the mass flow rate of coolant (water), C_p is the specific heat of coolant, ΔT is the temperature difference between outlet and inlet of the coolant.

The experimental thermal conductivity of the heat pipe obtained by the Fourier heat conduction equation is shown below

$$k_{eff} = Q \frac{L_{eff}}{A \Delta T} \tag{1}$$

where, Q is the heat transfer rate, ΔT is the temperature difference between the evaporator and condenser and L_{eff} is the effective length of heat pipe. The effective length of the heat pipe is expressed as

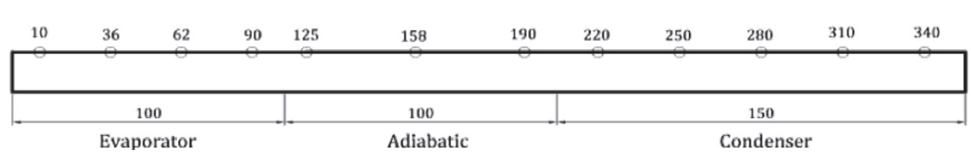

Fig. 2. Thermocouple position of heat pipe.