An experimental investigation of heat pipes at low power inputs

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Abstract:

In most precision engineering applications, minimization of thermal distortions is done by the use of either active control using temperature controlled air or liquid showers, artificial heaters or ultra low expansion materials such as Invar, Zerodur. This paper explores the use of heat pipes at low heat loads (0.1 W – 5 W) in precision engineering applications where the requirement of stable and near uniform temperature is stringent. Experiments are performed on a commercial heat pipe and its performance characteristics such as effective thermal conductivity, transient response and temperature gradient at steady state are determined.

Introduction:

The process of miniaturization of existing technologies to the nano and micro level with applications in medical sciences, aerospace, communications, automobiles, electronics have put a tremendous demand for higher accuracy on the manufacturing processes and their concerning metrology. Of all the sources of inaccuracy in a precision machine tool, thermally induced distortions are the most prominent source of error and fortunately they are not random errors. These distortions are worsened by the increase in automation in precision machine tools and instruments since the gauging system is now thermally connected to the heat sources of the machine tool and also its dimensions are large compared to the manual gauging. It is a well-known fact that mitigating the thermal errors in machine tools results in increase in accuracy of the process by an order of magnitude and also improves the repeatability of the process. These effects can be reduced in 3 ways: (a) Compensation (b) Temperature controlled coolant shower (c) Passive cooling using heat pipes, heat sinks.

Compensation requires a thermal deformation model of the machine tool to determine the thermal displacements in real time and to account for these displacements in the process. Unfortunately most of the models that have been developed are either very complex and slow or very simple and inaccurate and do not represent the full range of the operating conditions. Also it is very difficult to compensate for the bending mode of deformation by using the position control system of machine tool.

Temperature controlled coolant shower method is widely used in machine tools since it is very simple to implement and has fast response. It has the added benefit of keeping the work area clean of chips, dust and other extraneous materials, which act as heat source or corrosion agent. Depending on the amount of heat removal and on the requirement of dry work area, the coolant can be air or fluid. Liquid shower has high heat capacity and therefore remove heat under near isothermal conditions thus minimizing thermal

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distortions. On the other hand, air shower is better in reducing the effect of external heat sources on the machine tool. It has been found out that in the machine tools, the process of pumping the liquid coolant alone generates a significant amount of heat and acoustic vibration. Bryan et al [1] reports that for the production of mirror finishes a structural motion of less than 2 μ inches is required in the machine tool.

Passive cooling by heat pipes and heat sinks are effective at high operating temperatures and high heat flux. This paper explores the use of heat pipes as a means of passive cooling at low power inputs encountered in the lithography process and other precision engineering applications to maintain stable, very low temperature gradients across the surface. The effective thermal conductivity of heat pipes and the transient response of the heat pipe are determined for different heat inputs ranging from 0.1 W to 5 W at the operating temperatures of 0 C and 17 C respectively.

Experimental Apparatus:

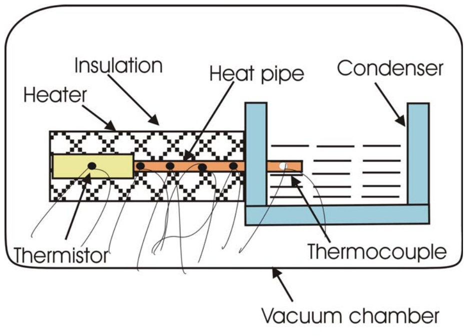

Fig 1. Schematic of the experiment setup

A 4 mm diameter circular copper water heat pipe of length 125 mm from Noron Products with thermistors along its length is insulated as shown as in the Fig 1. A 5W flexible kapton heater (Watlow) is wrapped around the heat pipe at one end. The other end of the heat pipe is inserted into the condenser. A thermocouple is glued 17 mm from the end on the condenser section of the heat pipe. This entire set up is then placed in a vacuum chamber to further reduce the heat loss through convection and radiation to the surrounding environment. The lengths of the condenser and the evaporator sections are 57 mm and 43 mm respectively. The temperature of the condenser was allowed to vary + 0.5 deg C in the case of freezing water (0 deg C) and ± 0.5 deg C in the case of the tap water (17 deg C) to simulate the real life conditions.

Results & Discussion:

The effective thermal conductivity, transient response, steady state temperature distribution of the heat pipe at 0 deg C and 17 deg C respectively are plotted in figures 2-7. The effective thermal conductivity of the heat pipe was found to be equal to that of copper at 0.4 W and 0.1 W of power input at 0 deg C and 17 deg C respectively. The heat pipe time constant was found to be ranging from 60 to 70 secs for both the cases thus indicating that the transient response was independent of the operating temperature of the heat pipe at low power inputs. The temperature gradient along the adiabatic section of the heat pipe at steady state was found to be varying linearly from –0.068 deg C /mm to –0.28 deg C/mm at 0 deg C and from –0.03 deg C/mm to –0.26 deg C/mm at 17 deg C between power inputs 0.1 W to 5 W respectively. This shows that the temperature gradient is not very sensitive to the operating temperature of the heat pipe.

The conductivity of OFHC copper is approximately 380 W/m-K. With heat flux levels as low as 1 W, the effective thermal conductivity of a heat pipe is several times that of a solid conductor.

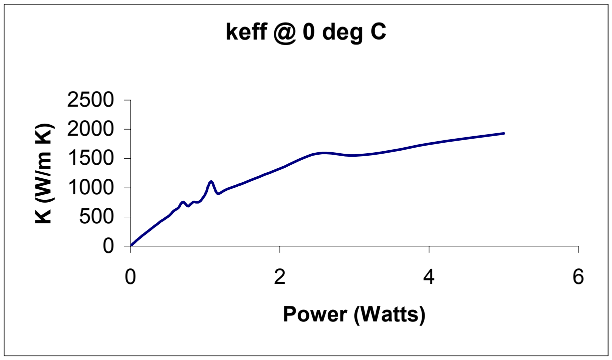

Fig 2. Effective conductivity at 0 deg C.

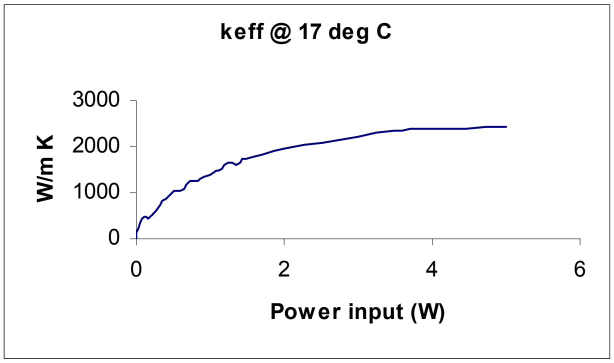

Fig 3 Thermal conductivity at 17 deg C

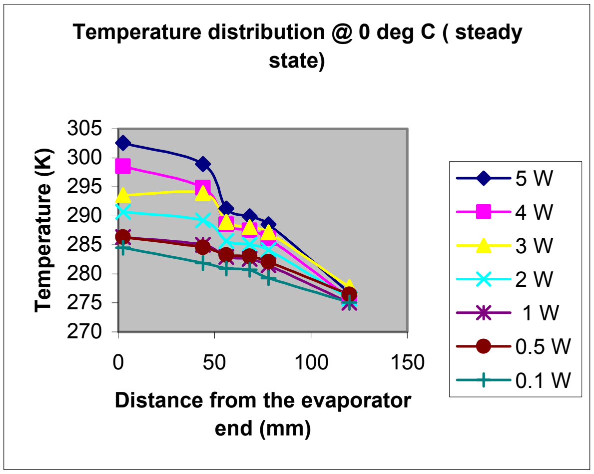

Fig 4 Temperature distribution at 0 deg C

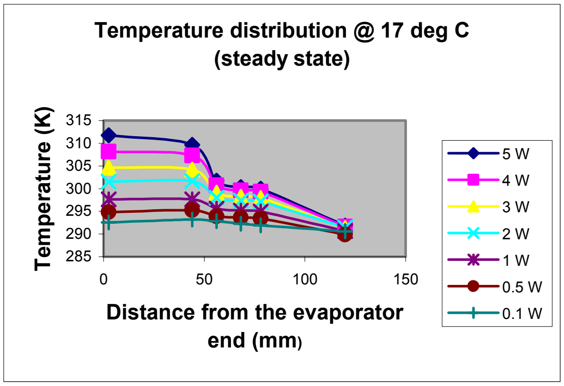

Fig 5 Temperature distribution at 17 deg C

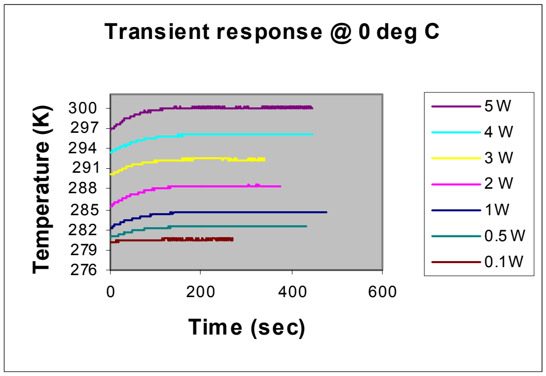

Fig 6 Transient response at 0 deg C

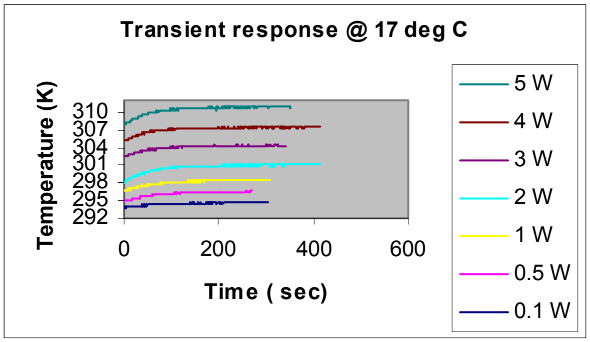

Fig 7 Transient response at 17 deg C

Conclusion:

The effective thermal conductivity, transient response and temperature gradient of the heat pipe at low power inputs were evaluated. From the results we conclude that heat pipes respond quite well in transporting randomly varying low heat loads which occur either due to friction between components in motion or due to concentrated heat input in case of the lithography process at stable temperature gradients. In the future, this would open up the possibility of manufacturing precision equipments by using a structure combining a structure with desirable mechanical properties with heat pipes and active thermal control to minimize thermally induced strain.

References:

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