Proceedings of HT2003
ASME Summer Heat Transfer Conference
July 21-23, 2003, Las Vegas, Nevada, USA

HT2003-47096

Thermal Performance of Heat Pipe Drill: Experimental Study

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ABSTRACT

An experimental study is performed in this paper to verify the concept of thermal management of using a heat pipe in the drilling process. The basic idea is to insert a heat pipe at the center of the drill tool with the evaporator located close to the drill tip, and condenser located at the end of the drill. In this way, heat accumulated in the drill tip can be transported to the remote section of the drill and remove it there to the tool holder, which attaches the drill. Temperatures at the drill tip as well as tool wear can be reduced significantly. In this paper, experimental investigations on a heat pipe drill for various heat flux inputs, inclination angles and rotating speeds are presented. The effect of contact resistance and tool holder (acting as heat sink) on heat pipe performance will also be demonstrated. The results presented in this paper may be used for important design and practical implementation considerations

INTRODUCTION

Even though application of heat pipes for a drill tool was mentioned in the literature (Marto, 1984), to the authors's best knowledge, there are no studies available on this particular application. Although the heat pipe literature is very extensive, rotating heat pipes with a wick structure has not received adequate attention in the past. The wick structure can provide a driving force to return the liquid to the evaporator even in horizontal drilling where gravity does not contribute. Most previous investigation in rotating heat pipes has used a Nusselt-type analysis for the liquid film (wickless heat pipes) (Ballback, (1969), Daley, (1970), Daniels and Al-Jumaily, (1975), Gray (1969), Harley and Faghri (1995)). Peterson and Wu (1991) present a review of rotating and revolving heat pipes. They indicate that the performance of rotating heat pipes without an internal taper is mainly affected by rotating speed, working fluid fill ratio, properties of the working fluid, working temperature, inclination angle and wick structure. In rotating heat pipe with an internal taper, the rotational speed was found to be the most significant parameter. Daniels and Al-Jumaily (1975) carried out an investigation of the factors affecting the performance of a rotating heat pipe. The authors performed a theoretical analysis of the condensation process using a Nusselt-type approach. Their analytical results were validated with experimental data for rotational speed between 600 and 1200 rpm using Acton 113 and Acton 21 as working fluid. They concluded that the rotational speed enhances the heat transfer capability, but the rate of increase of heat transfer tends to decline indicating an upper speed limit. Harley and Faghri (1995) studied a two-dimensional rotating heat pipe with transient effects, numerically. They also accounted for the vapor pressure drop and the interfacial shear stress of the counter flowing vapor. The interfacial shear stress was calculated directly. Schmalhofer and Faghri (1993) developed a three-dimensional model for an axially rotating heat pipe. A conjugate heat transfer problem, including the heat transfer in the vapor flow and the heat transfer in the liquid-wick region, was solved numerically. In their model, they assumed that the heat transfer in the liquid-wick region is pure conduction, and that a steady state solution can be established. The symmetry condition was imposed along the pipe cross-section to reduce the computer memory used and the computational time. Katsura, et al. (1987) performed experimental investigation on a wickless rotating heat pipes using water as working fluid. They concluded that the condenser performance increases with increasing rotating speed and increasing inner diameter. Reddy, et al. (1987) studied experimental performance characteristics of a wickless rotating heat pipe for different heat input, rotational speed and inclination angles. They concluded that thermal response varies drastically with the rotational speed and when the heat pipe is slightly inclined to the horizontal, large temperature fluctuations and instabilities occur. It is worth pointing out that for a heat pipe with a wick structure, the physical mechanism of heat transfer is different and the effect of the rotational speed on heat pipe performance was not very significant. Rotational speeds do have a great impact in the hydrodynamics of the vapor flow. However, for drilling applications the pressure drop in the vapor is very small and the vapor can be assumed isothermal. This was found from previous numerical studies (Gutierrez, 2002).

In any machining process, most of the mechanical energy is converted into heat in the cutting zone. This results in an increase in tool and workpiece temperatures. Elevated temperatures can significantly shorten the tool life. Excessive heat accumulated in the tool and workpiece can contribute to thermal distortion and poor dimensional control of the workpiece. In addition, high tool temperatures promote the formation of BUE (build-up edge) on the tool tip. In a drilling process, tool temperatures are particularly important because the chips that absorb much of the cutting energy are generated in a confined space and remain in contact with the tool for a relatively longer time compared with other machining operations. In drilling processes, cutting fluids are commonly used to perform the cooling of the drill and reduce the temperature in the cutting area. However, pollution and disposal problems have coerced the industry to look for new ways to remove heat efficiently. Heat pipes offer an effective alternate to conventional methods of removing heat from a drill tip, allowing drilling processes to operate in a dry and environmentally friendly fashion.

A heat pipe is a device that can transport thermal energy with relatively low temperature gradients with no external power supply. It uses the latent heat of vaporization of the working fluid to bring the heat from the evaporator to the condenser, which gives a very high equivalent thermal conductivity compared with a simple solid model of pure conduction. The idea of using a heat pipe for cooling a drill tool is inserting a heat pipe in the center of the drill. For drilling applications, putting an internal heat pipe has some manufacturing constraints. For example, the heat pipe location cannot get too close to the drilling tip, and the contact resistance between the heat pipe and the drill tool becomes very significant (Jen, et al., 2002).

In this paper, experimental investigations on a heat pipe drill for various heat flux inputs, inclination angles and rotating speeds are presented. The effect of contact resistance and the tool holder (acts as heat sink) in the evaporator section on the heat pipe drill performance will also be demonstrated. The results presented in this paper may be used for important design and practical implementation considerations

THE PHYSICAL MODEL

The idea of using a heat pipe for cooling a drill tool is shown in Figure 1. For drilling applications, putting an internal heat pipe has some manufacturing constraints. For example, the heat pipe location cannot get too close to the drilling tip, and the contact resistance between the heat pipe and the drill tool becomes very significant (Jen, et al., 2002a). In this study a drill of 0.75 inch (19.05 mm) in diameter and 9.725 inches (247 mm) long was used. A heat pipe of 0.25 inch (6.35 mm) was inserted into gun-drilled hole carefully. From thermal point of view, the closer the heat pipe to the external surface of the drill, the better the heat transfer performance. However, there are geometric and stress constraints that require keeping the heat pipe smaller. Finite element analysis, modeled the heat pipe as a constant surface temperature allows performing parametric studies on the effect of the internal diameter on maximum shear stresses (Jen et al., 2002b). Based on this analysis, a heat pipe of 0.25 inch (6.35 mm) was used for this study. Having a heat pipe a high effective conductivity, the conduction heat transfer mechanism is essentially a radial conduction process. The contact resistance between the heat pipe and the drill contribute to the temperature drop in the drill and it is important to be able to reduce it as much as possible. For the thermal purpose, the closer the heat pipe to the tip, the better the heat transfer rate. The effect on the stresses was not very significant. However, from practical considerations, a certain distance has to be left if regrinds are required. For all these considerations, the heat pipe was placed approximately 1.0 inch (25.4 mm) away from the tip.

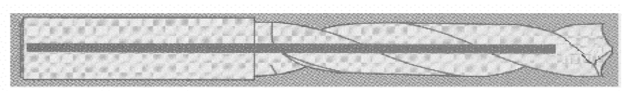

Figure 1 - Location of the heat pipe inside the drill

EXPERIMENTAL SETUP AND PROCEDURE I: for different heat flux inputs

An experimental study was performed first in a steel solid cylinder and in a steel cylinder of the same dimension with a heat pipe inserted into it (See Fig. 2). These solid steel cylinders have the dimensions of 6.0 inches long and 1.0-inch diameter. The heat pipe used is 0.5 inch in diameter and 6.0 inches long. It was inserted into the steel cylinder until 1.0 inch away from the base of the cylinder. The hole was 1.0 mm larger than the diameter of the heat pipe. This gives a clearance of 0.5 mm between the heat pipe and the drill. In general, the smaller the clearance, the better heat transfer performance is. However, cares must be taken to ensure the film distributes uniformly to minimize the contact resistance. The cylinder was maintained in a furnace until reach 600 ^{o}C approximately. A certain amount of tin material was melted in the hole of the cylinder to create a good contact between the heat pipe and the drill inner wall. Note that the tin metal has a melting point of 232 ^oC, much lower than the carbon steel but a thermal conductivity of 66 W/m-K, comparable to the conductivity of the steel. The melted tin material creates a pool of a liquid metal at the bottom of the drill hole. The heat pipe was slowly introduced until get the bottom of the hole. In order to create a uniform film between the heat pipe and the drill in the region where most of heat is transported, portion of the drill that is acting as the evaporator is reheated to approximately 600 ^oC again. This allows forming a continuous film and reducing the contact resistance. To study the effect of a holder acting as a heat sink, a solid disc of 5.0 inches diameter and 1.0 inch thick was attached to the condenser section (see Fig. 3). Four thermocouples were attached to the evaporator section, the adiabatic section and the condenser section. All thermocouples connected to a data acquisition system. A section of 1.5 inches was inserted in a radiant heater (i.e., evaporator section), 4.5 inches of the adiabatic section was insulated and an air blower was used to remove the heat from the remaining 1.5 inches (i.e., condenser section, see Fig. 4). For the solid cylinder, the thermocouple in the evaporator was placed 0.5 inches from the bottom of the cylinder, two thermocouples in the adiabatic section at 2.5 inches and 3.5 inches from the bottom and the other in the condenser section at 0.5 inches from the top. From the temperature difference at the adiabatic region, the heat input was calculated using the Fourier's law. For the cylinder with a heat pipe, two thermocouples were placed in the condenser, one on the heat pipe and the other on the external surface of the holder. Only one thermocouple was placed in the adiabatic region, right in the middle of that section. The heater was connected to a variac that allows controlling the heat input into the cylinder. For this system, experiments were running only in the vertical position, for two different heat input.

Figure 2 - Steel solid cylinder with and without a heat pipe

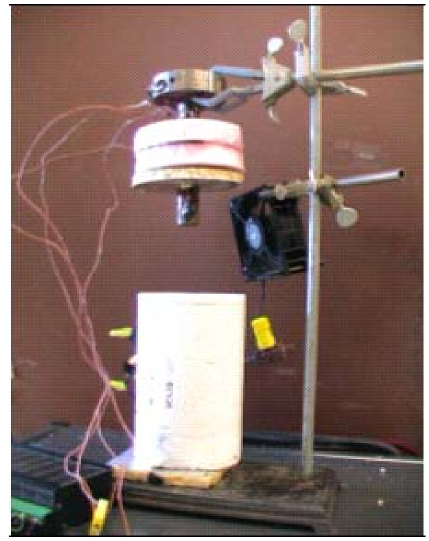

Figure 3 - Experimental Setup

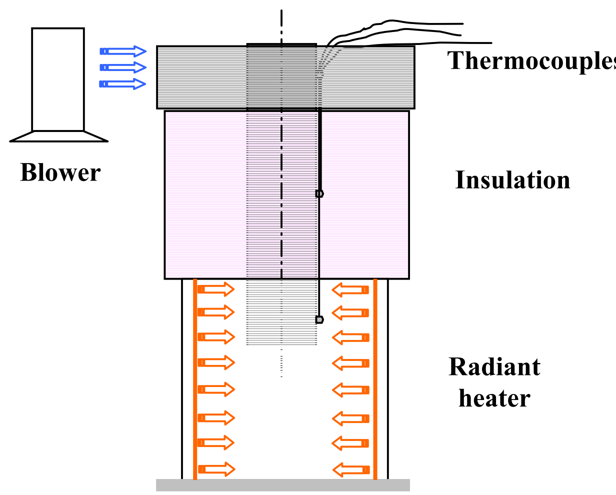

Figure 4 - Schematic of the experimental setup

RESULTS AND DISCUSSION

Let's describe briefly the fundamental mechanisms of a heat pipe drill under drilling operations. The heat is generated at the tip due to the cutting process, transferred by conduction to the heat pipe that is acting as a heat sink. The input heat flux vaporizes the liquid in the wick and carried away by the vapor due to latent heat of vaporization to the condenser where it condenses and releases the latent heat that is transferred by conduction to the tool holder and by convection to the surrounding. It is difficult to have a good access to the cutting region, which is confined by the workpiece, but it is easier to have better access to the condenser section. Reducing the temperature in the condenser area will reduce the operational temperature of the heat pipe and consequently the temperature on the tip. The larger the diameter of the heat pipe the larger the area in the evaporator section and the higher the heat power that can be applied before reaching the capillarity limit. However, geometric and stresses considerations constrain the diameter of the heat pipe.

Figure 5 shows a comparison of the temperature history between the solid cylinder and the cylinder with the heat pipe inserted in it. For a heat input of 31 W, it can be seen that the heat pipe cylinder (red symbol) has much lower temperature in the evaporator section. Compared to solid cylinder, it can be seen that, the temperature at the evaporator section (i.e., cutting tip) of the heat pipe cylinder is 52°C lower (148 ºC and 96 ºC for solid cylinder and heat pipe cylinder, respectively). However, in the condenser region, the solid cylinder temperature is 55°C, which is lower than the heat pipe cylinder, which is at 65°C. This is no surprising since more heat has been transported to the condenser section in the heat pipe cylinder due to latent heat. It is also observed that the maximum temperature difference between the evaporator and the condenser is 93 ºC for the solid cylinder and 33 ºC for the heat pipe cylinder. This shows how the heat pipe redistributes the thermal energy making the system more "isothermal". As observed in Figure 5, the transient time is much shorter in the heat pipe cylinder (3000s compares to 6000s for solid cylinder), this is simply because the system has less heat capacity to store energy and thus respond faster. The heat pipe reduces the maximum temperature in 35 % respect to the maximum temperature in the solid cylinder.

Figure 6 shows a comparison of the temperature history between the solid cylinder and the heat pipe cylinder, with a heat input of 56 W. Again, the trend is similar to the previous case but in this case the maximum temperature for the solid cylinder and the heat pipe cylinder is 359 ºC and 226 ºC respectively, with a temperature reduction of 37 %. The maximum temperature difference (for evaporator and condenser section for the same cylinder) in this case is 263 ºC and 100 ºC for the solid cylinder and cylinder with the heat pipe respectively. Numerical studies have shown that the heat pipe behaves more isothermally with some temperature drop due to the wick structure, where the effective conductivity is small and the assumption of a constant temperature provided by the heat pipe is a good assumption (Gutierrez, 2002). However, the operation temperature (the temperature in the adiabatic section, which is approximately the vapor temperature) is controlled by the heat input and the heat removal boundary condition at the condenser. It was shown that the operational temperature increases with the heat input, for the same convection condition (Gutierrez, 2002).

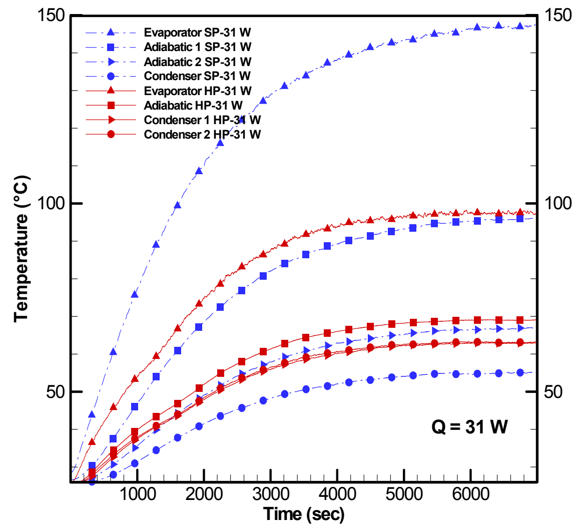

Figure 5 - Comparison of temperatures between a solid cylinder and a heat pipe cylinder with a heat input of 31 W.

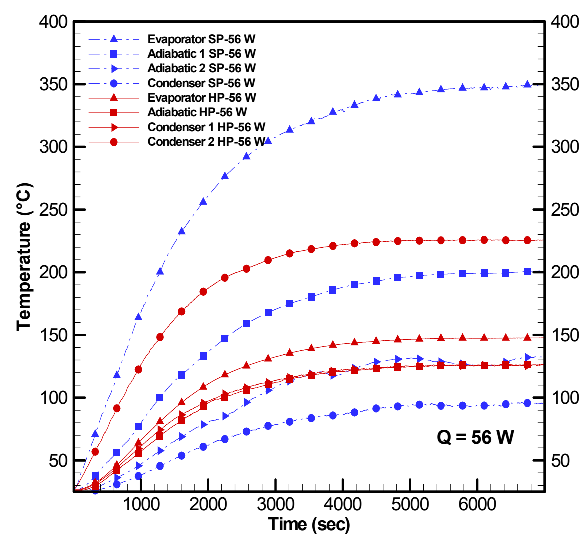

Figure. 6 - Comparison of temperatures between a solid cylinder and a heat pipe cylinder, with a heat input of 56 W.

EXPERIMENTAL SETUP AND PROCEDURE II: for different inclination angles and different rotation speeds

An experimental study was performed in a real drill and in a real drill of the same dimension with a heat pipe inserted into it (See Fig. 7). These real drills have the dimensions of 8.0 inches long and 0.8-inch diameter. The heat pipe used was 0.5 inch in diameter and 6.0 inches long. The procedure to insert the heat pipe into the drill was identical to the procedure for the cylinder with a heat pipe. In order to test the effect of different orientation, the experimental setup was mounted on a movable worktable, which can be rotated at different angles (see Fig.8). Two thermocouples were attached on the evaporation zone and adiabatic zone for both drill and drill with heat pipe. All thermocouples were passed through the bearing and then were connected to a slip ring. By connecting channels from slip ring to data acquisition system, temperature data can be recorded continuously.

Test Parameters:

- Rotating speed: 0 rpm (Stationary)
  600 rpm
  1000 rpm

- Orientation: Horizontal
  Vertical

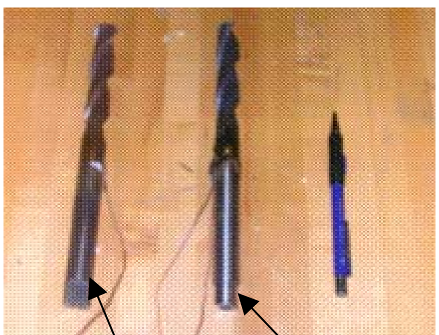

Figure 7 - Drill and drill with heat pipe

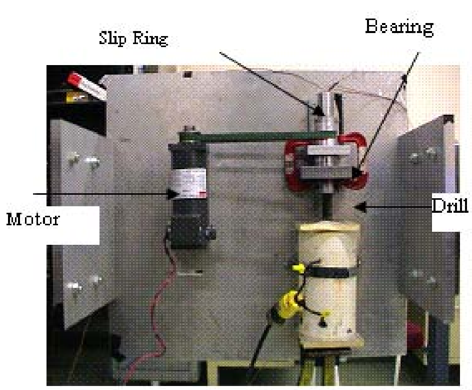

Figure 8 - Experimental setup

Figures 9 through 11 show the comparison between the temperature distribution in a solid drill and a drill with heat pipe for heat input of 56 W with a rotational speed of 0 (stationary), 600 rpm and 1000 rpm, respectively. From Figures 9, 10 and 11, it can be seen that the temperature decreases around 24% at the evaporation zone for all three different rotating speed (i.e., 0 rpm, 600 rpm and 1000 rpm) when a heat-pipe drill is used. Almost no effect of rotating speeds on the temperature at the evaporator section is observed.

Figure 12 shows the temperature distribution of the drill with the heat pipe at different rotating speed under the same heat input condition, 56W. At the rotation speed of 0 rpm (stationary), the temperature of the evaporation zone is 354.160 ^{o}C, and the temperature under the same conditions at rotation speed 600 rpm, 1000 rpm are 347.129 ^{o}C and 340.324 ^{o}C respectively. These results obviously show that there's essentially no effect of the rotating speed variation on the temperature. This has been further confirmed by numerical simulation (Gutierrez (2002)).

Figure 13 shows the transient temperature responses of a heat pipe drill at different orientations. At heat input of 56 W and rotating speed of 600 rpm, the steady state temperature at evaporation zone (drill tip) under vertical orientation and horizontal orientation is 288.062 ^{o}C and 347.129 ^{o}C respectively. This indicates that the heat pipe drill performance decreases as the drill orientation changes significantly from vertical to horizontal. This is no surprise since gravity is aiding the liquid flow back to the evaporator section in the vertical orientation. In Figure 14, the heat input at the evaporator section is still 56 W and rotation speed is now increased to 1000 rpm, the steady state temperature of evaporation zone under vertical orientation and horizontal orientation is 297.441 ^{o}C and 340.324 ^{o}C, respectively. Both results show that the temperatures of the evaporator zone at vertical orientation are 10%~15% lower than the temperature at horizontal orientation and the rotating effect is essentially negligible. It is also worth to note that from both figures, the horizontal heat pipe drill actually performs better when it is under transient condition. This may suggest that when the drilling time is not very long, the horizontal drilling process may have even better performance than the vertical orientation. By all these results, it is noted that the performance of heat pipe drill is better in vertical orientation than horizontal orientation under steady state condition and that is mainly because the gravity force helps quicker return of the fluid to evaporator and hence speed up the heat exchange process.

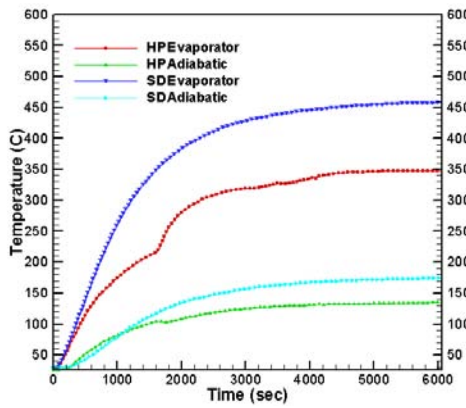

Figure 9 - Heat pipe effect under stationary condition.

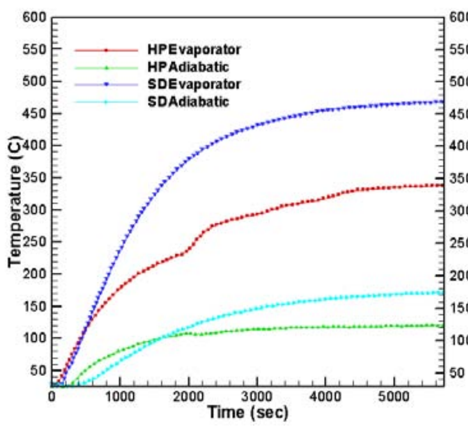

Figure 10 - Heat pipe effect under 600 rpm operation speed.

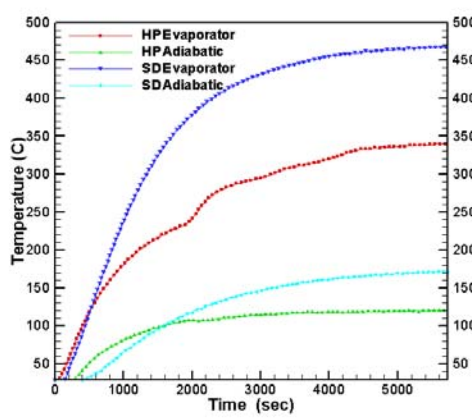

Figure 11 - Heat pipe effect under 1000 rpm operation speed

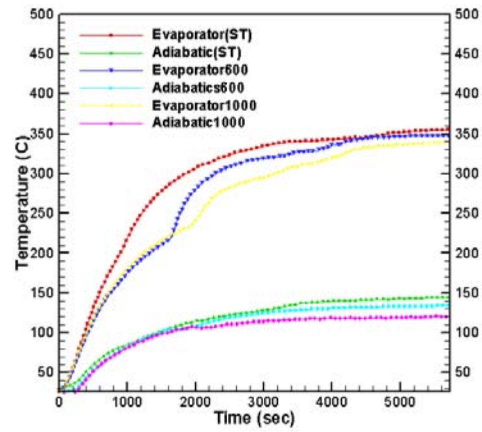

Figure 12 - Effect of different rotation speed on the drill with heat pipe

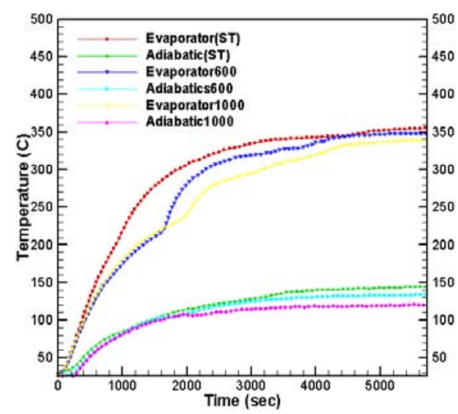

Figure 13 - **Effect of different orientation on drill with heat pipe under 600 rpm operation speed**

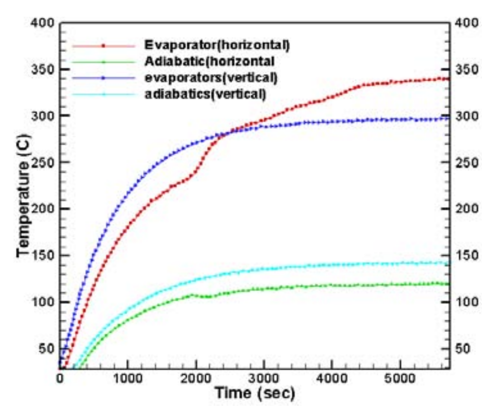

Figure 14 - Effect of different orientation on drill with heat pipe under 1000 rpm operation speed

CONCLUSIONS

From the above-described experimental study, several important conclusions emerge:

- From the comparison of the solid cylinder and the heat pipe cylinder, significant temperature reduction in maximum temperature in the evaporator is achieved. Even higher temperature reduction can be obtained using a larger diameter heat pipe.
- The heat pipe cylinder responds faster than the solid cylinder and behaves more "isothermally" with much lower temperature difference between the evaporator and the condenser sections.
- From the comparison of solid drill with the heat pipe drill, the temperature reduction is very significant, of the order of 41 % in the vertical position and 31 % in the horizontal position.
- From the comparison of different rotation speed of the drill with heat pipe, the temperature difference between different rotating speeds is very small. The effect of rotation could be neglected accordingly.
- The results of temperature distribution under different orientation show that the gravity force plays an important role at the vertical operation, which could decrease the temperature of evaporation zone by 13 %.
- These experimental results confirm the potential of heat pipe technology as an effective alternative to removing heat from a drill tip.

ACKNOWLEDGMENTS

Dr. Tien-Chien Jen, Dr. Gustavo Gutierrez and Mr. Yau-Min Chen would like to thank the National Science Foundation (through NSF-GOALI DMII-9908324), Lamb Technicon Machining Systems and UW System Applied Research Award for their financial support of the project. The authors also like to thank Mr. Rajendra Jadhav, Mr. Jeff Gehlhoff and Miss Fern Tuchowski (All three of them are supported by NSF-REU supplement) for their collaboration in the experimental tests.

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