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Heat Pipe Turbine Vane Cooling

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P28 Heat Pipe Turbine Vane Cooling

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Abstract

The applicability of using heat pipe principles to cool gas turbine vanes is addressed in this beginning program. This innovative concept involves fitting out the vane interior as a heat pipe and extending the vane into an adjacent heat sink, thus transferring the vane incident heat transfer through the heat pipe to heat sink. This design provides an extremely high heat transfer rate and an uniform temperature along the vane due to the internal change of phase of the heat pipe working fluid. Furthermore, this technology can also eliminate hot spots at the vane leading and trailing edges and increase the vane life by preventing thermal fatigue cracking. There is also the possibility of requiring no bleed air from the compressor, and therefore eliminating engine performance losses resulting from the diversion of compressor discharge air. Significant improvement in gas turbine performance can be achieved by using heat pipe technology in place of conventional air cooled vanes. A detailed numerical analysis of a heat pipe vane will be made and an experimental model will be designed in the first year of this new program.

Introduction

The heat pipe itself was first formally proposed for use in thermionic applications by George Grover of Los Alamos in 1963. Since then it has been shown that it is a heat transfer device that can exhibit an extremely high effective thermal conductivity, much greater in fact than any known homogenous material. A typical heat pipe (Faghri, 1995) is shown in Figure 1. In operation it is essentially a constant temperature device. It consists of a closed container in which vaporization and condensation of a fluid take place. The choice of a fluid depends on the temperature range in which the heat pipe will be used; e.g. for gas turbine application, sodium or lithium could be used. Heat added at one end of the container causes evaporation of liquid into vapor. Condensation of the vapor along the cooled end (condenser) of the

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container maintains the container surface at a nearly constant temperature. The resulting condensate is returned to the heated end (evaporator) of the container by the action of capillary forces in the liquid layer which is contained in a wick lining the inside of the cavity. A typical wick might consist of layers of metal screen or some porous metallic structure.

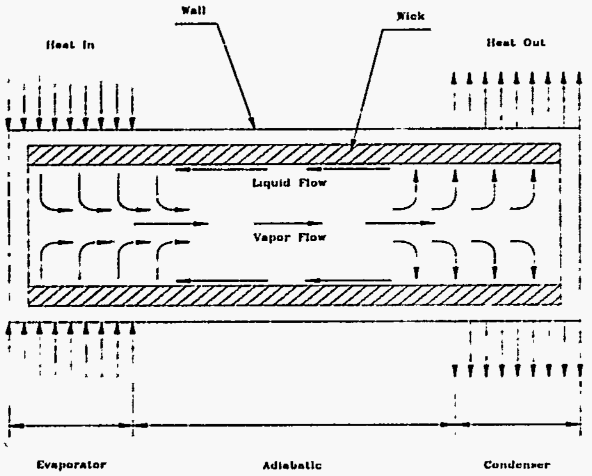

Figure1 :Heat pipe operation

Two heat pipe characteristics , its near constant temperature operation and its tremendous heat transfer ability (Faghri, 1995), make the heat pipe, if configured as a turbine airfoil, very attractive for high temperature gas turbine use. The idea of using it as a vane or stator (the 20,000 - 30,000 g acceleration fields typically generated in a rotating turbine blade limit it to stator use) in a turbine has been considered by some gas turbine specialists over the years. For instance one of the authors (Langston) proposed its use as a stator in 1964 and did a study of its use in a military jet engine (Langston, 1968), using the results of some preliminary 1967 liquid sodium heat pipe vane experiments done by SNECMA, the French jet engine manufacturer. Also, Silverstein (1992) did a preliminary analysis as part of a first phase investigation in conjunction with the United States Air Force and the Allison Gas Turbine Division of General Motors.

These, two rather limited heat pipe vane studies we are aware of have dealt with military or other high performance jet engines, (i.e. aviation gas turbines). Military engines have high turbine temperatures suitable for heat pipe applications, but they must operate with high maneuver loads (a 10 g dive or turn might adversely affect capillary pumping in a heat pipe vane) and a minimum of weight (heat pipe vanes could add some small amount of weight). The feasibility studies done to date have shown promising results, but not promising enough for jet engine manufacturers to make use of heat pipe vanes in a production engine. This is mainly due to the lack of experimental simulation and detailed design analysis.

Land based gas turbines are stationary (no maneuver loads) and therefore weight is not a major consideration. Thus our program differs from those of the past in its application to stationary shaft-power gas turbines rather than to maneuvering, thrust-power aviation gas turbines. Furthermore, a detailed experimental and numerical/analytical program including actual testing of a heat pipe vane will be started in this one-year contract and proposed for completion in the next year.

Problem

All modern high temperature turbines are cooled for the most part by bleeding relatively cool compressor air from the gas path and then reintroducing it in the turbine in such a way as to cool turbine airfoils (blades and vanes) that are in the hottest regions of the turbine. There are two general types of turbine vane cooling: 1) Internal convective cooling and 2) film cooling.

Internal convective cooling is used to cool the inside surfaces of a turbine vane. The cooling air usually exits at the vanes trailing edge. This leads to a thick trailing edge, which increases the turbine aerodynamic losses.

Film cooling is used for the highest turbine temperatures, especially for gas temperatures that significantly exceed the melting point of the nickel based alloys used to make vanes. Cooling air from the compressor is injected onto the gas path surface of the vanes, to form a protective layer of cool gas, shielding the vane from the hot gas path flow. Film cooling leads to aerodynamic losses in the turbine because of the disruption it causes in the gas path. There are many overall disadvantages of air cooling of turbine vanes and a few are as follows:

- There is an added cost of producing the turbine vanes in the machining of the internal passages and/or surface conditions.

- Turbine vane reliability is significantly reduced with the machining of the internal passages which can lead to mechanical stress concentrations.

- Turbine vanes have high losses associated with the thicker geometric design associated with internal passages.

- The injection of cooling air (especially for film cooling) into the gas path leads to aerodynamic losses through disruption of the gas path flow and through the mechanisms of mixing.

- Air cooled vanes are not isothermal and the resulting metal temperature gradients lead to thermal fatigue and cracking.

Approach

Use of heat pipe vane cooling for a turbine promises improvements in overall gas turbine durability and performance by at least one of three ways:

1) The isothermalization of vanes thereby minimizing thermal stresses.

2) Reduction of the amount of turbine cooling air required, thereby improving turbine efficiency or increasing the amount of cooling air available for NO_x control.

3) Removing turbine cooling air injection gas path sites, thereby reducing turbine aerodynamic losses.

For example, consider the simplest case of isothermalization of a vane. Suppose a turbine vane is operating under temperature conditions such that it needs no net cooling, but the designer has used convection cooling because of burner "hot spots" (earlier versions of the first vane of the JT8D fits this description.) By making such a vane into a heat pipe (no net cooling air required), it will be "isothermalized" with the hot spots cooled by heat pipe action with the heat being transferred to the colder parts of the vane. The vane surface acts as both evaporator and condenser for the heat pipe.

For the case of an existing cooled vane, we will consider three methods of fitting the turbine vane with a heat pipe. Other designs may result from the work proposed here. Option #1 is a conventional heat pipe turbine vane (Figure 2), Option #2 is a double-walled heat pipe turbine vane (Figure 3) and Option #3 is an annular heat pipe turbine vane (Figure 4). All three options will have the same overall characteristics in the operation of the heat pipe. First, the evaporator section of the heat pipe fitted turbine vane will be the section that is in direct contact with the combustion gas while the condenser section is actually an extension of the turbine vane into a passage that contains a stream of cooler air flow that acts as a heat sink. All three heat pipes will consist of a wicking material such as layered screens or a sintered porous material. The working fluid can be a high temperature substance such as liquid sodium or lithium.

The reader will possibly recall that the use of a liquid metal in a power plant is not new. Liquid sodium has been used in exhaust valves of high performance internal combustion engines for years. The differences of the three options are in the variety of heat pipe types and materials that are fitted into the turbine vane. These differences and correct procedure for the selection of working materials and fluids will be carefully considered.

Option #1, conventional heat pipe, is the simplest in theory and application. The turbine vane is fitted with a wick structure that covers the entire interior surface of the vane. The wick structure is saturated with the working fluid, i.e., sodium or lithium at ambient conditions. The turbine vane corresponds to the evaporator section of the heat pipe. During operation, the turbine vane is exposed to the combustion gas stream which vaporizes the working fluid in the wick. The vapor will then flow towards the condenser section where the fluid will condense back to its liquid form releasing the latent heat of vaporization energy into the heat sink.

The choice of the heat sink for the heat pipe vane is dependent on the particular application, and will be one of the things to be studied in the work proposed here. As an example, consider the case of the first vane (the nozzle). One can design the heat pipe evaporator section to extend into a cavity below the first vane ID platform (and forward of the first disk), into which cooling air from the compressor is introduced. The cooling air flows into the cavity, cools the heat pipe evaporator, and then could be reintroduced into the gas path at the first vane's platform leading edge. Another possibility is to exhaust the heated cooling air directly onto the first blade, in such a way as to attempt to control secondary endwall flow effects from the first vane. Other possible heat sinks include an air or stream closed loop system, where the vane heat removed from the gas path is returned to the cycle in a regenerator. Certainly other possibilities exist for effective heat pipe vane heat sinks in other gas turbine configurations such as the HAT cycle.

Option #1 is attractive since the interior of the vane does not have a cooling flow of air that is diverted from the compressor discharge directly into the gas path. This option allows uniform temperature along the turbine blade surface during and would allow the hot spots such as the leading and trailing edges to be sufficiently cooled. The temperature gradients along the surface would be reduced significantly, reducing the chances of thermal stress induced cracking. Overall, the heat pipe would still remove a much higher amount of heat then would a one phase flow of air as in existing conventional methods.

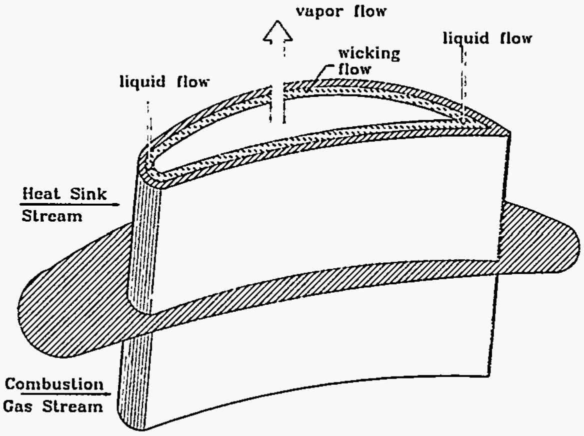

Figure 2: Conventional heat pipe turbine vane design (Option #1)

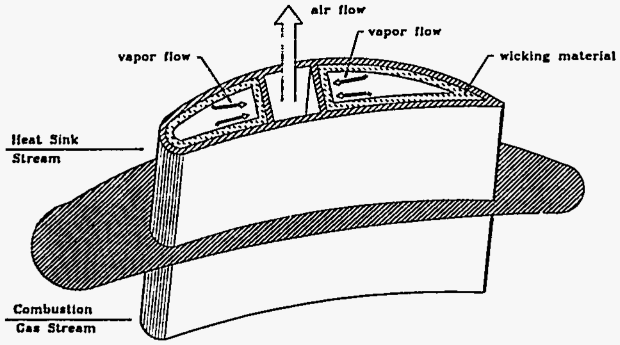

Figure 3: Double wall heat pipe vane cooled by heat pipe effect and internal air stream (Option #2)

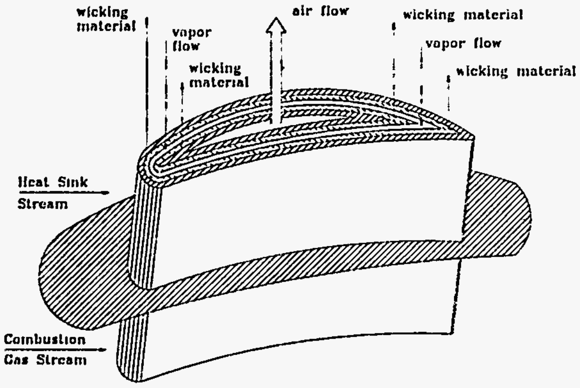

Figure 4: Annular heat pipe turbine vane cooled by heat pipe effect and internal air stream (Option #3)

Option #2, the double-walled heat pipe turbine vane, would also help reduce the hot spot temperatures at the leading and trailing edges and allow the surface of the blade to maintain a more uniform temperature at extremely high heat flux designs. Figure 3 shows the operating principle behind this option. Two separate heat pipes would be fitted into the turbine vane at theleading and trailing edges. The heat generated at the leading and trailing edges would conduct through the turbine and into the wick structure, where the working fluid would be vaporized. The vapor would then be transported to the heat adjacent heat sink as in Option #1. The difference in this option comes from the internal air flow passage in the turbine vane. This air flow is diverted from the compressor as in existing cooling methods. Overall, the high conductive heat pipes are positioned to concentrate on the removal of heat from the leading and trailing edge hot spots while the internal air flow is positioned to remove heat from the surface where the temperatures are lower. This would allow for a more uniform blade surface temperature, leading to a less likelihood of a surface temperature gradient which could result in thermal stresses. Option #2 may be useful, but as can be seen, the controlling heat transfer resistance is in the air flow passage.

Option #3, the annular heat pipe turbine, is another promising method of removing heat from the turbine blade surface and also will help the liquid to be returned to the evaporator. The operating principle behind the annular heat pipe turbine blade is very similar to Option #1 but allows for more surface area for the removal of heat. As shown in Figure 4, this annular heat pipe geometry consists of an internal air flow passage. The wick structure is placed on both the inner wall of the turbine vane and the outer wall of the air passage. The evaporator section of the turbine vane would remove heat from the combustion gas stream and vaporize the working fluid. However, with this option the vapor starts to condense close to the evaporator end of the turbine vane. This allows the evaporator section to absorb more energy from the surface. As the remainder of the vapor travels along the length of the vane it is continuously condensing into the wick structure and finally at the condenser end both wall surfaces act as a heat sink. This option allows the condensate to be returned to the evaporator end at a higher and more efficient rate then any of the other methods. Also, the capillary limit of this annular heat pipe is greater then a conventional heat pipe. A slight disadvantage exists in the fitting of the complex annular heat pipe geometry.

There are significant advantages of these proposed heat pipe turbine vanes over ones using conventional cooling techniques. Some of these are:

- The extremely high heat transfer rate of the heat pipe operating principle due to the change of phase. The removal of heat by latent heat of vaporization of a liquid metal is many order of magnitudes higher then that of conventional convective or conductive methods.

- Uniform temperature along the vane surface is accomplished by fitting the turbine vane with a heat pipe. With existing, conventional techniques of cooling turbine vanes the temperature distribution along the surface of the vanes is not uniform due to the difficulty, or impossibility, of running air cooling passages through the thinner parts of the turbine vane. With heat pipe fitting of the turbine vanes, this is not a concern.

- Elimination of hot spots at vane leading and trailing edges due to the very high effective heat transfer coefficients.

- There are no aerodynamic losses due to the injection of cooling air into the gas path. This in itself could increase the efficiency of an existing high temperature turbine by 2-4 percentage points (e.g. an 88% turbine going to 92% efficiency).

The one disadvantage that is foreseen at this time is the added weight of the turbine vane due to the greater length. However, this is of concern in aviation applications. A feasibility study done on an advanced military fighter turbine engine, showed an increase in engine weight of only 1% (Silverstein and et al, 1994).

One other possible disadvantage is the heat (energy) the heat pipe vane may remove from the gas path and hence the cycle, as discussed in Option #1. There are ways that this heat could be reintroduced back into the cycle, depending on the location of the vane and on the particular cycle under consideration.

Project Description

The time has come to do an in depth study and evaluation of the heat pipe vane for land based shaft power producing gas turbines, for the following reasons:

1) The turbine inlet temperatures of modern land based gas turbines are now approaching those of high performance jet engines. The application of an advanced cooling scheme such as the heat pipe vane would be ideally suited to the stationary installation of such machines. Performance gains beyond the standards set by jet engines might be possible with the elimination of compressor cooling air in the hot turbine gas path.

2) Over thirty years of research and development have vastly improved heat pipe performance and manufacturing. One of the authors, Dr. Faghri, is a noted heat pipe researcher and has just published a text on the latest developments in the field of heat pipe science and technology (Faghri, 1995).

Thus we are strongly convinced the time is right to seriously consider the use of heat pipe vanes for land based shaft power producing gas turbines. In this one year contract we will set out on a three part program whose objectives are as follows:

1) Numerical/Analytical Simulation Study.
To develop a detailed numerical/analytical simulation model to predict the performance characteristics of heat pipe vanes under various heat load distributions. What is the predicted transient performance of a heat pipe vane? What happens during engine startup and shut down? What are the heat transport limitations? No detailed transient numerical simulation accounting for the nonconventional geometry of the turbine vane has been done in the past.

2) Experimental Study:
To develop an operating map for a heat pipe vane subjected to engine temperatures and heat loads. This will answer such questions as which geometries and materials are the most promising, what are performance limits and how isothermal is the heat pipe vane. No such experimental results are presently available in the open literature.

3) Gas Turbine Manufacturer Design System Study:
Given the overall characteristics of a heat pipe vane and the results of 1) and 2) above, what does the design system used by a gas turbine manufacturer predict for performance gains in a modern gas turbine using heat pipe vanes? What stages in a turbine are best suited to heat pipe applications?

Efforts on all three of these objectives will be carried out during this one year contract. A proposal for a future contract will then be submitted, based on the first year results.

Acknowledgements

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