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Experimental Evaluation of a Turbine Blade with Potassium Evaporative Cooling

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A new method of turbine blade cooling, the return-flow cascade, was developed in which vaporization of a liquid metal such as potassium is used to maintain the blade surface at a nearly uniform temperature. Turbine blades cooled using this technology may have lower blade temperature levels than those available with conventional air cooling and could result in higher firing temperatures or a choice of a wider range of materials for the hot-gas path. Condensation occurs remotely from the blade and enables heat rejection to alternative sinks such as low-pressure air or fuel. Experimental results are presented from testing of a potassium-cooled model blade in the rotating heat transfer rig at the Massachusetts Institute of Technology. An infrared detector capable of high scan rates was used to fully map the temperature distribution of a single heated rotating turbine blade. The functioning of the cascade is inferred from this temperature distribution and shows that a near-uniform blade temperature can be maintained by the evaporative cooling system.

I. Introduction

ALL modern high-performance jet engines use air cooling of the turbine to enable operation at firing temperatures well above the limits set by turbine materials. Air is drawn from the compressor discharge, routed through the interiors of both the nozzles and first-stage rotating blades, and cools the blades by convection on the interior and by film cooling on the exterior surfaces. Such convection- and film-cooling systems enable operation at firing temperatures as much as 1000 K above metal temperatures. They also, however, impose limits on permissible turbine inlet temperatures for a number of reasons. As compression ratios are raised along with turbine inlet temperatures to improve efficiency, the cooling-air temperature increases and the amount of available air decreases. This places greater demands on the effectiveness of the air cooling and on the precision with which the heat transfer to the blade can be predicted during the design process. Together, these constraints impose limits on the turbine inlet temperatures that can be employed with air cooling to achieve acceptable engine performance.

Vaporization cooling via the return-flow cascade (RFC) was conceived as a means to address these limits. The concept consists of cooling the blade by internal vaporization from a film of fluid distributed on the internal surface of the blade, the vapor being condensed remotely from the blade and returned to the point of evaporation. This is the mode of operation of heat pipes, in which wicks or other fine structure return the liquid to the points of evaporation and distribute it by capillary pumping. But capillary effects are too weak to distribute the liquid radially in the strong centrifugal force field of a rotating turbine blade. In the RFC, the radial flow of the liquid from the condenser and its distribution over the internal surface of the blades is accomplished by means of a series of shelves that cause the liquid to cascade successively from the innermost to the outermost shelf, driven by the radial force field. The result is the formation of a film covering the internal surface of the blade, just as the wick maintains a film on the interior of the heat pipe. Locally varying heat fluxes cause vaporization to occur at different rates, but as long as the total amount of fluid in the system is adequate, fresh fluid will flow into the hot spots and maintain a nearly constant temperature over the entire blade surface. In this manner, the RFC is a self-regulating cooling method. This process is illustrated in Fig. 1.

Two putative advantages accrue. First, the self-regulation of the cascade mitigates the need for accurate prediction of the heat-flux distribution to the blade, maintaining a uniform blade temperature, independently of variations in the heat flux from the hot gas to the blade. Second, the condenser can be cooled by other means than compressor discharge air (for example, by lower-pressure air or fuel), potentially enabling higher pressure ratios.

II. Background

Soon after the development of the gas turbine in the late 1930s, the need for turbine blade cooling was recognized. As early as 1940, researchers at the NASA Lewis Research Center (now NASA John H. Glenn Research Center at Lewis Field) were exploring internal air cooling, transpiration cooling, film cooling, and natural convection liquid cooling [1]. One of the earliest published proposals for liquid cooled turbine blades was made by Schmidt [2] in 1951, based on work he had done in Germany during World War II. His proposal was an open thermosyphon in which liquid water was fed into a hollow rotor and then through radial holes into the turbine blades. In 1955,

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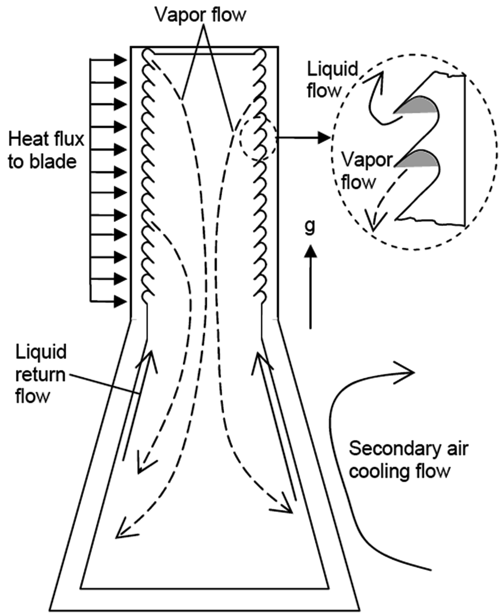

Fig. 1 Conceptual drawing of the return-flow cascade.

Cohen and Bayley [3] reviewed several types of liquid cooling and commented that the two-phase closed thermosyphon "in which a quantity of liquid is enclosed within each blade to act as a conveyor of heat to the more easily cooled root" was the most suitable method for cooling turbine blades. They also noted that liquid metals would be an attractive choice of working fluid due to the fact that the internal operating pressure would be close to 1 atm at expected blade temperatures, although their testing was done only with water, butyl alcohol, and chlorobenzene.

In the 1960s, methods to cool turbine blades using compressor bleed air were introduced into practice. These methods have a major advantage over liquid cooling in that the coolant is supplied from, and can be rejected to, the engine core airflow. Air cooling has been the dominant cooling method since that time.

There have, however, been many analytical and experimental studies of liquid cooling in the last 40 years. Gray [4] proposed a wickless rotating heat pipe that was integral with the shaft of the engine and would deliver liquid through radial passages to the turbine blades for cooling. The shaft would have a slight internal taper at the condenser end such that the centrifugal force drives the condensate back toward the evaporator end. This scheme is similar to Schmidt's [2] early work, except that it is a closed-loop cooling system. Gray [4] also focused on the effect of centrifugal acceleration on the phase-change processes in the heat pipe.

Work has also been done on the static two-phase closed thermosyphon, which operates at 1 g (9.81 $\mathrm{m/s^2}$). The rotational-acceleration levels in a rotating turbine blade are much higher than 1 g, but these studies provided the groundwork for future investigations of rotating thermosyphons. Many of the lessons learned from these early studies were used in the design of the RFC. Lee and Mital [5] performed tests on a static two-phase thermosyphon and explored the effect of fill volume on maximum heat flux. They found that there is a maximum fill volume above which there is no additional advantage in terms of increased heat-flux capability. Imura et al. [6] developed a correlation for the critical heat flux of a static two-phase closed thermosyphon. They determined that the critical heat flux for flow through small tubes is smaller than that for pool boiling. Hong et al. [7] theoretically determined that the negative effects of noncondensable gases on condensation in a static thermosyphon are decreased at a higher system temperature.

A number of experimental and theoretical studies of rotating two-phase thermosyphons were done with the purpose of understanding the effects of heat flux, rotational-acceleration thermosyphon geometry, and noncondensable gases on the heat transfer performance. One of the first published analyses of a rotating two-phase closed thermosyphon using a liquid-metal cooling was done by Genot and LeGrives [8]. They examined the vapor–liquid interaction under high centrifugal forces and also examined the effects of heat flux, rotating speed, and cooling-airflow rate experimentally in an evacuated rotating rig at moderate and high rates of rotation. They also confirmed that a two-phase thermosyphon is capable of dissipating the heat fluxes expected in gas turbine engines. Chato [9] investigated the phase-change heat transfer of the film condensation layer in the condenser of a static two-phase closed thermosyphon. Ling et al. [10] derived closed-form solutions for the liquid-film distributions in the condenser section and the vapor-temperature drop in the evaporator section of a radially rotating miniature thermosyphon at rotational speeds on the order of those found in gas turbine engines. They determined that the internal diameter, the rotating speed, and the operating temperature can affect the performance of the thermosyphon. Ling and Cao [11] then modified their analysis to include the effect of noncondensable gases. Finally, Ling et al. [12] tested their theoretical results by testing miniature rotating thermosyphons with a diameter on the order of 1 mm and measured the effects of heat flux, cooling-airflow rate, rotation rate, and internal diameter. A similar experimental study was also done by Waowaew et al. [13]. These studies on rotating thermosyphons prove that the concept of vaporization cooling as implemented in a thermosyphon is viable for turbine blade cooling.

Kerrebrock and Stickler [14–17] performed the first experimental work on the RFC. They tested a cylindrical model with shelves that were axisymmetric about the radial direction coupled to a conical condenser, with water as the working fluid. They were able to achieve a nearly constant temperature (within 20°C) between the evaporator and condenser and also found that the cascade has some self-regulating capability.

All of the aforementioned experimental work was done using geometrically simple models. Ling et al. [12] and Waowaew et al. [13] both used a cylindrical thermosyphon, and Genot and LeGrives [8] used a flat parallelepiped model. The heat load in these studies was supplied by resistive heating through the model. In addition, temperature measurements were taken via surface-mounted thermocouples.

The present study contains the first reported surface-temperature measurements of a resistance-heated rotating turbine blade using the RFC technology. The model geometry is representative of an actual turbine blade, and the heat flux to the blade is simulated to reflect the actual chordwise heat-flux distribution seen in a gas turbine. This choice was driven by the desire to demonstrate effective RFC cooling at blade leading and trailing edges, as well as near the midchord, with realistic local heat-flux levels.

III. Experimental Apparatus

The system studied is a turbine blade with an integral air-cooled condenser. The main goal of the testing was to demonstrate the effective operation of the RFC in a heated rotating turbine blade. Heating of the turbine blade is accomplished by resistive heating of the blade skin. The blade contour was selected to represent current turbine-engine-blade technology and is shown along with some nominal dimensions in Fig. 2. The blade span is 3.5 cm. The nominal blade skin thickness is 0.05 cm (0.02 in). The actual blade skin thickness varies around the perimeter of the blade to allow the resistive heating to create a heat-flux profile similar to that found in modern gas turbine engines. The heat flux and blade skin thickness are shown in Fig. 3.

The internal wall of the turbine blade is lined with 27 capture shelves (spaced 0.05 in apart) from hub to tip that trap the liquid coolant. The shelves are continuous along the entire inside perimeter of the blade to allow the liquid-coolant level to equilibrate in each shelf. There are nine overflow ports in each shelf that allow the coolant to flow to the next radially outward shelf. The overflow ports are offset from shelf to shelf to prevent a continuous stream of liquid flow to the tip, bypassing the shelves. A baffle was fit against the internal contour of the shelves to prevent the liquid from flowing directly to the tip without being distributed in the shelves. The baffle

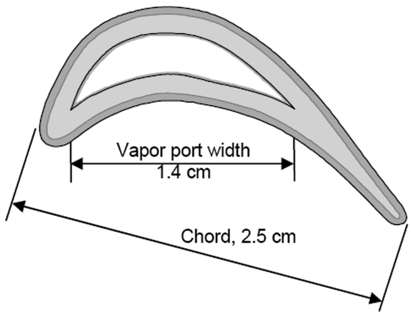

Fig. 2 Blade contour showing size of vapor port.

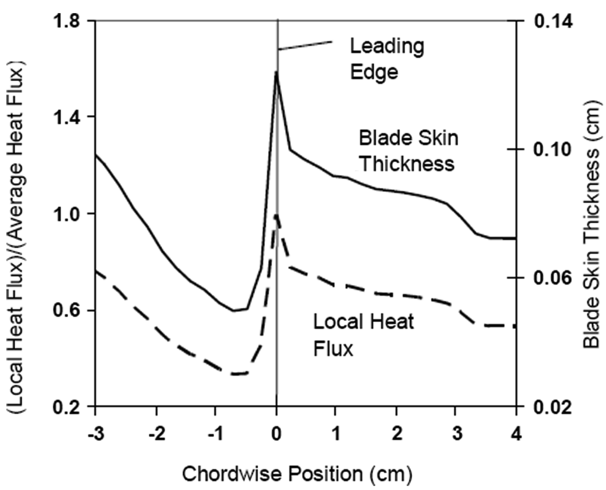

Fig. 3 Heat-flux distribution around the perimeter of the blade as determined by the blade skin thickness.

has six vapor ports at each radial shelf location to allow the evaporated potassium to flow into the center port of the blade. The blade is welded to the condenser, which is rectangular in cross section and is externally air-cooled.

The vapor–liquid transport processes are illustrated in Fig. 1 (the baffle is not shown). Liquid potassium flows up the condenser walls, driven by rotational acceleration, and into the blade. The liquid fills each shelf and then flows through the liquid-overflow ports (not shown), fills the next shelf, and continues filling all the shelves up to the tip of the blade. Liquid evaporates from the shelves and the vapor flows through the vapor ports in the baffle and then flows radially inward through the blade center port and is condensed on the condenser walls. Cooling-airflow enters the condenser housing, then flows through small air passages along the two sides of the condenser and out on the opposite side. The condenser was designed to provide adequate cooling for this proof-of-concept experiment and is not representative of a design that would used in an engine.

Potassium was chosen as the coolant because of its high heat of vaporization, its vapor-pressure characteristics, and its wetting ability. The vapor-pressure curve for potassium indicates that at a typical average blade temperature (1050 K), the corresponding equilibrium vapor pressure at which evaporation will occur is approximately 1 atm. The potassium fill amount was selected to give a tip pool with a depth of 0.05 in., after filling the shelves and providing for a liquid film in the condenser, and for the volume of vapor needed to fill the remainder of the empty space in the blade. The final fill amount calculated for potassium was 0.45 g, which corresponds to 4% of the void volume of the blade and condenser system. The fill process was designed to avoid the introduction of noncondensable gases, which would decrease vapor diffusion to the condensing surfaces and increase the overall temperature drop from blade to condenser.

All experimental work took place in the rotating heat transfer rig at the Massachusetts Institute of Technology (MIT) Gas Turbine Laboratory. This facility has been used for numerous turbine cooling studies over the past 25 years [18,19]. The blade model is mounted on the end of a 0.5-m rotating arm with appropriate counterweights on the opposite end. The rotor arm is enclosed in a tank, which can be evacuated to a pressure of 10^{-4} torr. This eliminates windage losses, minimizing the shaft power required to drive the unit, and avoids convective heat transfer from the test hardware. Although the rig is designed to operate up to speeds of 30 rps, the maximum speed for the current testing was 16.5 rps, due to the imbalance caused by transformers mounted on the rotating arm. This maximum rotational speed corresponds to a tip speed of 51.8 m/s.

The blade surface temperature is measured as a raster scan over the surface of the blade. The sensor is an Electro-Optical Systems HgCdTe infrared temperature sensor used in previous MIT experimental studies [11,12]. The IR sensor is contained in a chamber adjacent to the rotating arm chamber and is mounted on a two-axis movable platform. Two digitally controlled linear translators are used to locate the sensor in relation to the blade model as it passes by the open viewing window between the two chambers. The horizontal distance between the IR sensor and the blade is set at the optimal focus location at the beginning of a run and is not moved once the run has begun. The vertical stepper motor is exercised throughout the run to collect data over the entire blade surface from hub to tip. A constant feed of liquid nitrogen through the vacuum wall of the IR chamber is used to maintain the detector at the operating temperature of 217 K.

The BEI shaft-encoder index is set at an angular location such that it triggers the IR data acquisition just before the blade model reaches the viewing window. A telescope consisting of two spherical mirrors located on the IR platform focuses the signal from the blade onto the IR detection aperture. The IR system measures the incident radiation from a nominal area of 1 mm^2 on the blade surface. Two flat mirrors positioned on either side of the blade at 45-deg angles from the blade chord provide an optical path covering the entire blade perimeter on each rotational pass. As the blade rotates by the infrared detection window, the IR detector picks up the radiation from a single radial location across the entire perimeter of the blade. Before the next pass, the IR detector's vertical location (relative to the span of the blade) is incremented and data from a second radial location are collected. Through this process, a map of the radiation emitted from each 1-mm^2 area is measured. Radiation energy is converted to temperature using a previously obtained calibration curve.

III. Experimental Results

Effective operation of the RFC was observed at rotational speeds higher than 14 rps (radial acceleration of 395 g). Because of the speed limitations of the rotating heat transfer rig (16.5 rps maximum), a lower limit on rotational speed was found for effective cascade operation, but a high limit was not found during the testing. This low speed threshold is due to surface-tension limits in the liquid-overflow ports (designed to allow the liquid potassium to cascade from shelf to shelf). Increased rotational acceleration eliminates this problem. This result is in agreement with the modeling predictions of the RFC performance [20,21].

Effective operation of the cascade is defined as the case in which the standard deviation of the average temperature distribution over the surface of the blade is less than 50 K. When the cascade is not functioning as designed (typically, at rotational speeds less than 14 rps for this study), the maximum blade temperature is much higher than that of the condenser and has a maximum at midspan because the heat is being conducted to the support structure at the hub and tip. In this case, it is proposed that the liquid potassium is not flowing radially upward from shelf to shelf and that the resistive heating of the blade causes an increase in the temperature of the blade itself. At rotational speeds higher than 14 rps, the liquid potassium flows radially outward from shelf to shelf and becomes evening distributed in the shelves along the inner surface of the blade. The heat load to the blade causes the potassium to evaporate while more liquid potassium constantly refills the shelves. Therefore, the blade structure is maintained at a nearly uniform temperature.

To illustrate these two cases, temperature data from a single chordwise location (specifically, the midchord of the suction side of the blade) are plotted in Fig. 4, which highlights the radial variation from hub to tip. The difference between a conduction profile (11 rps) and cascade operating profile (14 rps) is evident in the shape of the curves shown in Fig. 4. When the cascade is operating, the condenser temperature (in this case, 760 K) and blade temperatures are much closer and the latter is nearly uniform. An error bar is shown for all the blade temperature measurements corresponding to an error of ± 18.2 K. The depression of the blade temperature at the hub is most likely due to the placement of a copper ground strap bolted to the condenser structure near the hub, allowing another conduction path at that point. No high-heat-flux limit traceable to the cascade performance was reached during testing.

Surface-blade temperature maps corresponding to the data shown in Fig. 4 are shown in Figs. 5 and 6. The data in these figures were collected during the same run, approximately 3 min apart. Both the pressure side and the suction side of the blade are shown, with the leading edge in the middle of the plot. The heating of the blade was held constant, and the only difference is the rotational speed of the turbine blade. In Fig. 5, the speed was 11 rps. As the speed was increased to 14 rps, the average temperature of the blade surface dropped (from 977 to 797 K) and the blade temperature became more uniform. The temperature drop can also be seen in the test timeline, shown in Fig. 7. As the rotational speed was increased beyond 11 rps, the average blade temperature dropped and the condenser temperature increased.

The global and most significant result is that the RFC functioned as designed in a rotating turbine blade with potassium as the coolant. Proper functioning was clearly distinguishable by a near-uniform blade temperature.

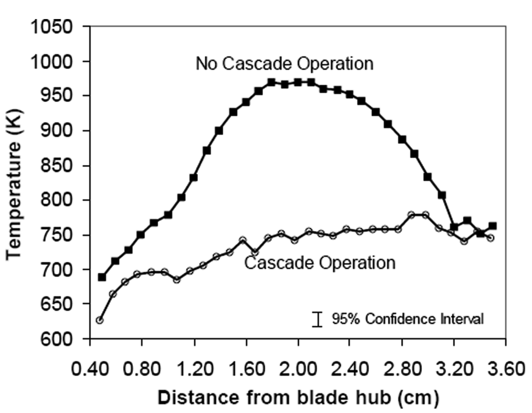

Fig. 4 Comparison of the temperature distribution on the suction side of the blade (midchord) for a case in which the cascade is not functional (11 rps) and a case in which the cascade is maintaining a more constant temperature across the blade (14 rps).

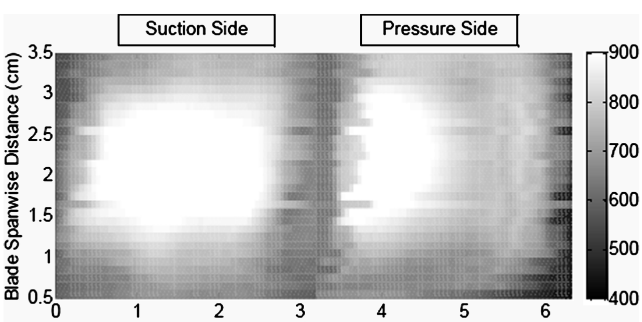

Fig. 5 Blade temperature map showing both the suction and pressure sides of the blade for a case in which the cascade is not operating (11 rps).

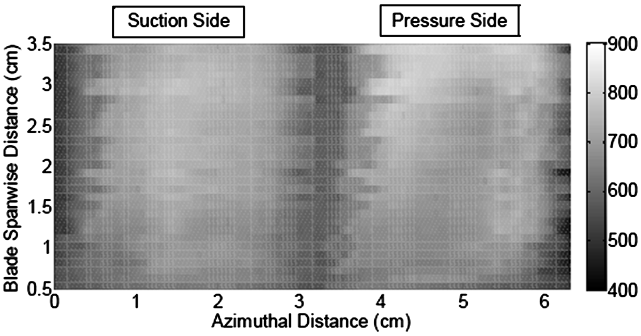

Fig. 6 Blade temperature map showing both the suction and pressure sides of the blade for a case in which the cascade is operation. The temperature of the blade is much more uniform than that shown in Fig. 5 (14 rps).

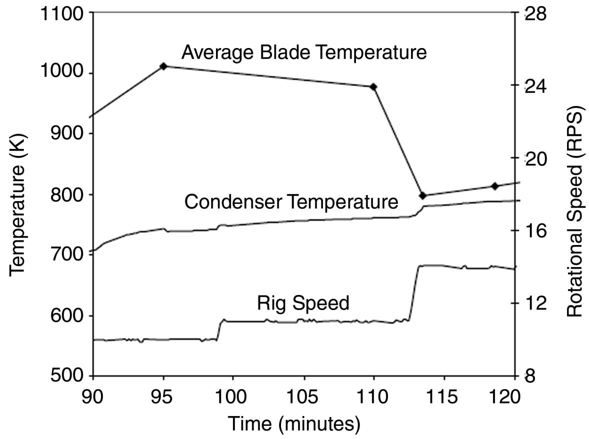

Fig. 7 Typical testing timeline showing how the increase in rotational speed reduces the difference between the blade temperature and the condenser temperature.

IV. Discussion of Results

In an evaporatively cooled turbine blade, a liquid metal is exposed to high heat fluxes and high radial accelerations as it undergoes processes such as pool boiling, evaporation, condensation, and liquid and vapor flow. In general, results from in-depth modeling and analysis of the vapor- and liquid-flow processes [20,21] were consistent with the behavior observed in the experiments.

The rotational accelerations at which tests were performed were much lower than what a turbine blade would encounter in an engine. Modeling results indicate that there is no upper limit on rotational acceleration for effective cascade operation. The lower limit encountered in the testing was confirmed with modeling. Specifically, the minimum rig rotational speed required for nonlimiting flow in the liquid-overflow ports predicted by the model (13.6 rps) matched well with the speeds at which cascade operation was first observed (14 rps). This limit could be decreased further by increasing the area of the liquid-overflow ports.

The heat fluxes achieved in these experiments were much lower than would be expected in a modern gas turbine. These were set by mechanical and electrical limits of the rig and were not limited by the functionality of the cascade. Previous experiments by Ling et al. [10] demonstrated heat-flux capabilities consistent with engine conditions in a cooled rotating heat pipe.

V. Engine Implementation

There are several benefits that would come from the implementation of the RFC in a gas turbine engine. First, the ability of the RFC cooling system to maintain the blade temperature at a nearly constant level would reduce the thermal stresses in the blade material and simplify the development process. Second, with conventional air cooling, all heat exchange to the air coolant happens in the turbine blade itself, and the RFC secondary heat exchanger could be located in the blade root or in the turbine disk. Condenser designs would not be constrained by the geometry of the blade and could use less compressor air, lower-pressure air, or even fuel as the coolant. Third, film cooling reduces the aerodynamic efficiency of the turbine, which can decrease the overall engine efficiency. The return-flow cascade as a form of internal cooling does not cause such losses. On the negative side, when film cooling is no longer used, the heat flux to the blade (and therefore the heat load on the return-flow cascade) is increased. A determination of the airflow required to cool the RFC condenser is needed to fully appreciate the savings in performance achievable with the return-flow-cascade technology. The combination of a more effective heat exchanger design, lower losses in the turbine, lower thermal stresses in the blade, and the possible addition of a thermal-barrier coating to the blade should allow for better engine performance at the current firing-temperature levels or should allow some margin to increase firing temperatures.

A. Blade Design

The experimental work presented here showed that the shelf design allows consistent cooling of the entire blade surface area, including the leading and trailing edges. Even though the heat-flux levels in the experimental work were low compared with engine conditions, the basic shelf design was proven to be effective in distributing liquid throughout the blade and could be used as a baseline design for turbine blades in an engine. The relatively simple internal structure of the evaporatively cooled blade would allow also for more freedom in turbine blade aerodynamic design.

B. Condenser Design

A major challenge in successfully implementing the return-flow cascade in a gas turbine engine is the design of the condenser. Compressor bleed air is the most likely secondary cooling fluid for the condenser heat exchanger, but other options such as lower-pressure air or fuel may be attractive for engine system reasons. In the experiment described here, the condenser was designed as an integral part of the blade root, although it was sized for the cooling-air availability of the test rig. An integral blade/condenser design seems the most likely configuration for any future engine testing. A detailed design of a bleed-air-cooled integral condenser was performed, and hardware design studies showed fully acceptable levels of stress.

C. Internal Coolant

Potassium was identified as the most feasible primary coolant for an engine, due to its high heat of vaporization and vapor-pressure characteristics. The long-term effects of steel and nickel alloys exposed to potassium have been studied [22], and there are no significant corrosion effects. It should be noted that liquid-metal cooling is common in nuclear reactors and in heat pipes without long-term damaging effects to the containment material.

VII. Conclusions

Vaporization cooling using the return-flow cascade is an effective method for turbine blade cooling in gas turbine engines. Compared with direct air cooling, vaporization cooling reduces or eliminates turbine aerodynamic losses and increases engine efficiency by reducing cooling airflow. The work described in this paper has proven the functionality of the return-flow cascade in a turbine blade geometry with an alkali metal coolant and provides the groundwork for further development of the system. Increased understanding of the internal two-phase processes in an evaporatively cooled turbine blade will provide a basis for optimal design of the internal structure of the blade. A demonstration of the return-flow cascade in a gas turbine engine is needed to lend credence to the viability of the technology for eventual implementation in gas turbines in service. An effort is currently underway through a Defense Advanced Research Projects Agency contract with Aerodyne Research, Inc. and the MIT Gas Turbine Laboratory to demonstrate the vaporization-cooling technology in a small gas turbine engine.

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