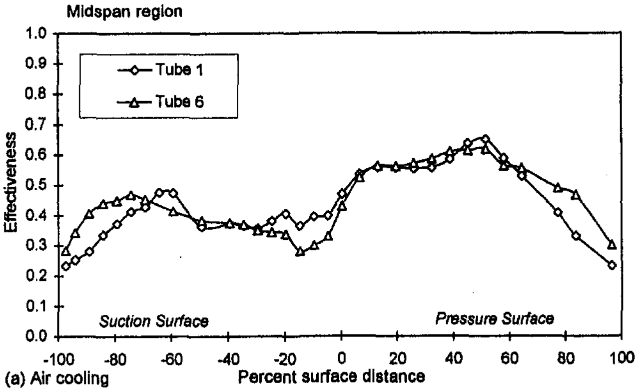
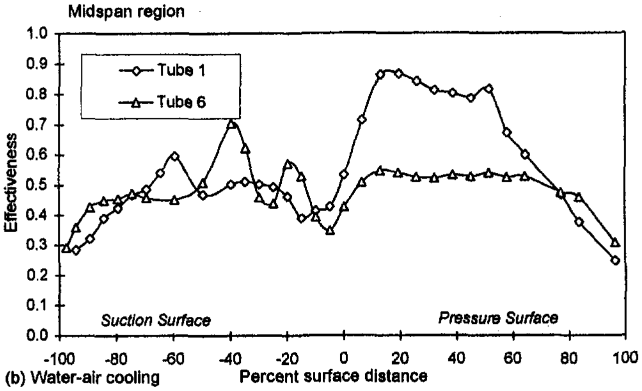
Impingement Tube Var	T_{gas}(°C): 676.7 Reynolds No.: 1.50E+06 Mach No.: 0.7	Air: 3% Water: 0.0%		
Average Effectiveness				
	Tip	Midspan	Hub	Overall
Tube 1	0.5596	0.4362	0.4586	0.4848
Tube 6	0.5105	0.4483	0.4475	0.4687



(a) Air cooling

Impingement Tube Var	T_{gas}(°C): 676.7 Reynolds No.: 1.50E+06 Mach No.: 0.7	Air: 3% Water: 0.4%		
Average Effectiveness				
	Tip	Midspan	Hub	Overall
Tube 1	0.7172	0.5512	0.5518	0.6068
Tube 6	0.5780	0.4896	0.4408	0.5028



(b) Water-air cooling

Fig. 19 Variation of the vane thermal effectiveness distribution with impingement tube hole pattern

overall heat transfer effectiveness. A variable impingement tube hole pattern was shown to provide higher overall effectiveness values than were obtained with an impingement tube with a uniform hole pattern.

It was also determined that the spray nozzle used for the water atomization plays a major role in the distribution of the water droplets and thus affects the heat transfer cooling effectiveness.

Though very high heat transfer effectiveness was achieved by this water-air cooling technique, uniformly high effectiveness values were not attainable. Nonuniformity seems to be attributed to poor water droplet distribution by the nozzle and the flow characteristics of two-phase flow in the gap region between the impingement tube and the airfoil inner wall. This study has demonstrated the outstanding potential of this cooling technique, but has also demonstrated that more work will be required to develop a coolant delivery system that has an adequately uniform cooling distribution.

Acknowledgments

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Impingement Tube 3	T_{gas}(°C): 676.7 Reynolds No.: 1.75E+06 Mach No.: 0.7	Air: 3% Water: 0.4%		
Average Effectiveness				
	Tip	Midspan	Hub	Overall
Nozzle 1	0.6779	0.6133	0.6087	0.6333
Nozzle 2	0.6915	0.5884	0.5736	0.6178

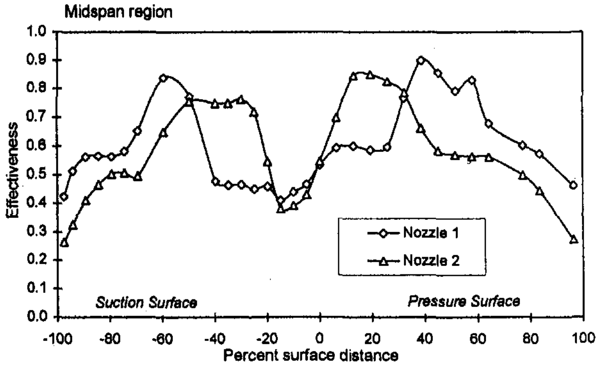

Fig. 20 Variation of the vane thermal effectiveness distribution with water nozzle

References

Biesiadny, T. J., Klann, G. A., Clark, D. A., and Berger, B. 1987. "Contingency Power for Turbo Small Turboshaft Engines Using Water Injection Into Turbine Cooling Air," NASA TM 89817, AIAA Paper No. 87-1906.

Dudley, J. C., Sundell, R. E., Goodwin, W. W., and Kercher, D. M., 1984, "Two-Phase Heat Transfer in Gas Turbine Bucket Cooling Passages: Part 1," in: *Heat and Mass Transfer in Rotating Machinery,* Metzer and Agfan, eds., Hemisphere Publishing Corporation, pp. 463–472.

Fiszdon, J. K., Florschuetz, L. W., and Janssen, J. M., 1994, "Heat Transfer to Two-Phase Air/Water Mixtures Flowing in Small Tubes With Inlet Disequilibrium," in: *Heat Transfer in Gas Turbines,* Chyu and Nirmalan, eds., ASME HTD-Vol. 300, pp. 165–171.

Hylton, L. D., Nirmalan, N. V., and Sweeney, P. C., 1995, "Advanced Cooling Concept," NASA Contractor Report, Preliminary Draft, Allison EDR 16666.

Kline, S. J., and McClintock, F. A., 1953. "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering,* Jan., pp. 3–8.

Nealy, D. A., Mihelc, M. S., Hylton, L. D., and Gladden, H. J., 1984, "Measurements of Heat Transfer Distribution Over the Surfaces of Highly Loaded Turbine Nozzle Guide Vanes," ASME *Journal of Engineering for Gas Turbines and Power,* Vol. 106, pp. 149–158.

Nirmalan, N. V., and Hylton, L. D., 1990, "An Experimental Study of Turbine Vane Heat Transfer With Leading Edge and Downstream Film Cooling," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 477–487.

Pedersen, C. O., 1970, "An Experimental Study of the Dynamic Behavior and Heat Transfer Characteristics of Water Droplets Impinging Upon a Heated Surface," *International Journal of Heat and Mass Transfer,* Vol. 13, pp. 369–381.

Schmidt, E., 1951, "Heat Transmission by Natural Convection at High Centrifugal Accelerations in Water-Cooled Gas Turbine Rotor Blades," *Institute of Mechanical Engineers Proceeding,* Vol. 185, pp. 219–222.

Sundell, R. E., Dudley, J. C., Grondhal, C. M., and Kercher, D. M., 1984, "Two-Phase Heat Transfer in Gas Turbine Bucket Cooling Passages: Part 2," in: *Heat and Mass Transfer in Rotating Machinery,* Metzer and Agfan, eds., Hemisphere Publishing Corporation, pp. 473–484.

Van Fossen, G. J., and Stepka, F. S., 1979, "Review and Status of Liquid Cooling Technology for Gas Turbines," NASA RP 1038.

Van Fossen, G. J., 1983, "The Feasibility of Water Injection Into the Turbine Coolant to Permit Gas Turbine Contingency Power for Helicopter Application," ASME *Journal of Engineering for Power,* Vol. 105, pp. 635–642.

Wenglarz, R. A., Nirmalan, N. V., and Daehler, T. G., 1995, "Rugged ATS Turbines for Alternate Fuels," ASME Paper No. 95-GT-73.

DISCUSSION

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I commend the authors for their investigation of a rather novel approach to the high-temperature turbine cooling problem. The

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method of suspended water droplets or "water mist" enhancement of air cooling would appear to offer some real promise once systematically characterized in terms of practical design variables. This work deserves high marks for originality, and several data trends in the paper are intriguing. However, little attempt is made to rationalize or systematically analyze those trends. Some specific comments follow:

1 A large amount of data is presented representing a considerable range of design and operational variables, but little attempt is made to interpret the data trends even in a first-order sense. The physical and geometric variables governing this cooling approach are undeniably complex and probably defy easy characterization. However, it is interesting to me that the broad trends with percent water injection (Fig. 11) almost behave as if latent heat of vaporization were not very important. If one would adopt the very simple-minded approach that the cooling effectiveness trends might be largely reconciled by defining a mass-average coolant mixture specific heat—ignoring latent heat of vaporization in the wall heat transfer process—the trends with increasing water content are surprisingly well predicted. If effectiveness, ϵ, is as defined in the paper, then one might argue from a simple energy balance perspective that, to first order,

$$R_m/R_a = (WCp)_m/(WCp)_a \qquad (1)$$

where

$$R = \epsilon/(1 - \epsilon)$$

and

$$W = \text{coolant mass flow}$$

$$Cp = \text{coolant specific heat}$$

The subscripts m and a denote air/water mixture and air, respectively. The mixture specific heat is simply defined as,

$$(Cp)_m = ((WCp)_w + (WCp)_a)/(W_w + W_a) \qquad (2)$$

where the subscript w refers to water.

Evaluating Eqs. (1) and (2) for the relative proportions of air and water in the experiment, overall effectiveness trends with increasing water content can be evaluated and compared to the data in Fig. 11:

Water percent	Overall effectiveness (Fig. 11)	Overall effectiveness (Eq. (1))
0	0.485	0.485 (baseline)
0.3	0.567	0.569
0.4	0.607	0.591
0.5	0.635	0.611

While I do not suggest that such a simple procedure—implicitly neglecting direct latent heat of vaporization as well as cooling channel thermal efficiency effects—represents a viable design tool, there is the clear suggestion that the cooling process may be largely driven by mixture specific heat level. It would at least be interesting to determine if similar broad trends exist for the other impingement geometries as well.

2 The overall effectiveness trends with air cooling alone (Fig. 12) seem surprisingly modest for a variation in cooling flow of two to one. Assuming an internal heat transfer Nu/Re power law relationship with a slope of 0.70, I would estimate that to first order, the overall effectiveness at an airflow of 4 percent should be at least 0.565, taking the 2 percent airflow case as a baseline.

3 I confess that I do not understand the trends in Fig. 14 at all. I would expect overall effectiveness to be relatively insensitive to T_g (or T_g/T_c) alone. The data suggest that reducing T_g from 816°C to 538°C increases the ratio R (as defined above) by an astonishing 65 percent! This implies a 65 percent increase in mean coolant side heat transfer coefficient (relative to gas side heat transfer coefficient) as T_g is reduced. It is not at all clear how such a profound effect is produced. Comparing this change in overall effectiveness (with T_g) to that shown in Fig. 12 (effect of cooling flow variation), the indicated percentage change in the ratio R is 50 percent greater than that which occurs for a two to one increase in cooling air flow! Also, the increase in R ratio with reduced T_g (65 percent) is essentially equal to that shown in Fig. 11 for an increase in water injection from zero to 0.4 percent (64 percent increase). While independent changes in gas to coolant (or gas to wall) temperature ratio have been shown to have a second-order effect on overall cooling effectiveness, the dramatic results in Fig. 14 are difficult to reconcile, particularly in light of the comment that T_g/T_c was fixed at 2.0 throughout the testing (p. 7).

In fairness, it should be noted that the last arguments are strictly valid for nominally gaseous, single-phase coolants. Thus the trends in Fig. 14 may in fact reflect some fundamentally different behavior unique to the water mist cooling approach. If so, this is a very important trend and perhaps deserves more discussion than it receives in the paper.

4 Finally, I am a little confused by the various repeated contentions that some type of optimal configuration, flow split, etc., may exist. I don't know that the data really suggest that. For example, the conclusion that "results indicate that there is an optimum coolant flow rate above which effectiveness increases are marginal" is somewhat careless use of the word "optimum." All internally cooled systems show monotonic increases in effectiveness with cooling flow, trends that tend to become asymptotic at very high cooling flow levels. However, I am not aware of any data that suggest a change in the sign of the slope of such trends.

Authors' Closure

We appreciate Dr. Nealy's comments. His observation that the manuscript did not address any analytical approach to rationalizing the data trends is valid. An attempt was made to give a physical basis for the trends of the various perturbations in the experimental program. The authors felt an analytical approach was not warranted in the scope of this work. A one-dimensional model of the heat transfer and flow of an air–water mixture in a channel had been previously developed at Allison Engine Company and would be ideally suited for this task. A response for each of Dr. Nealy's specific comments follows:

1, 3 The authors feel both concerns are related to the dependence of water cooling on the difference between the wall temperature and saturation temperature of the water. It is an interesting observation by Dr. Nealy that the sensible energy rise of air and liquid water based on the temperature increase of the coolant mixture approximates the sensible and latent energy changes in the actual mixture. At the lower temperatures at which the experiments were conducted, the latent energy change of the water may be a relatively smaller portion of the overall and hence the trend cited by Dr. Nealy compares well with the data. At the elevated temperatures of engine conditions, the authors feel this would not be the case. Further investigation would be warranted to examine this and other possible explanations of the data trends. Additionally, T_g/T_c was not fixed at 2 as stated by Dr. Nealy, but "was maintained at a typical engine ratio of about 2." T_g/T_c does vary some. The variation of cooling effectiveness with T_g again points to the dependence of water cooling on the temperature difference between wall and coolant.

2 For an impingement arrangement, the slope on the Nu/Re power law relationship varies between 0.7 and 0.9 depending on the spacing and Re number (Kercher and Tabakoff, 1970).