A Film-Cooling CFD Bibliography: 1971–1996

D.M. KERCHER*

GE Aircraft Engines, Turbine Airfoil Center of Excellence, 1000 Western Avenue MS 240-GH, Lynn, MA 01910, USA

(Received in final form 9 April 1997)

After more than 25 years of three-dimensional film cooling experimental investigations, analytical correlations and modeling, film cooling utilizing computational fluid dynamics has emerged from a similar development-applications growth process into a near-attainable heat transfer engineering tool. Analytical applications include high temperature subsonic to hypersonic flow with complex wall-geometry coolant injection film performance analysis techniques spanning usage from gas turbines to rocket engines to scramjets. In recent years there has been significant development in increased computer power and modeling capacity, increasingly more complex and successful Navier–Stokes turbulence modeling techniques, innovative labor-saving meshing techniques, and more successful validation of experimental results. These combined innovations have continued to transition computational film cooling technology from the academic, government and commercial research and development environment to the industrial design-analysis environment. This bibliography is an open-literature reference resource whose papers collectively describe the continual emerging of numerical film cooling as a viable design tool for high temperature components.

Keywords: Combustor cooling, Computational fluid dynamics, Film cooling, Gas turbines, Jets in crossflow, Rocket propulsion

1971–1979

Bergeles, G., 1976. Three Dimensional Discrete-Hole Cooling Process: An Experimental and Theoretical Study, Ph.D. Thesis, University of London.

Bergeles, G., Gosman, A.D. and Launder, B.E., 1976. The Prediction of Three-Dimensional Discrete-Hole Cooling Processes – Part 1: Laminar Flow, *ASME Journal of Heat Transfer*, **98**, pp. 379–386.

Bergeles, G., Gosman, A.D. and Launder, B.E., 1978. The Turbulent Jet in a Cross Stream at Low Injection Rates: A Three-Dimensional Numerical Treatment, *Numerical Heat Transfer*, **1**(2), 217–242; also University of California at Davis, Mechanical Engineering Department, Report FT/78/3.

Kreskovsky, J.P., Briley, W.R. and McDonald, H., 1979. Computation of Discrete Hole Film Cooling Flow Using the Navier–Stokes Equations, AFOSR-TR-79-0935.

* Tel.: 781-594-1802. Fax: 781-594-0935.

Matthews, L., 1971. Prediction of Film Cooling Effectiveness, in the Presence of Density and Pressure Gradients, by a Recirculating Flow Procedure, Imperial College of Science and Technology, Mechanical Engineering Department, EHT/TN/A/27.

Matthews, L., Rastogi, A.K. and Whitelaw, J.H., 1971. The Application of Numerical Methods to Film Cooling and Associate Practical Problems, *Proceedings of the 1st National Heat and Mass Transfer Conference*, India Institute of Technology, HMT-3-71, pp. V12–V19.

Patankar, S.V. and Spalding, D.B., 1972. A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-Dimensional Parabolic Flows, *International Journal of Heat and Mass Transfer*, **15**, pp. 1787–1806.

Patankar, S.V., Rastogi, A.K. and Whitelaw, J.H., 1973. The Effectiveness of Three-Dimensional Film-Cooling Slots – II. Predictions, *International Journal of Heat and Mass Transfer*, **16**, pp. 1673–1681.

Patankar, S.V., Basu, D.K. and Alpay, S.A., 1977. Prediction of the Three-Dimensional Velocity Field of a Deflecting Turbulent Jet, *ASME Journal of Fluids Engineering*, **99**, pp. 758–762.

1980–1989

Baker, N.R., Kamath, P.S., McClinton, C.R. and Olsen, G.C., 1988. A Film Cooling Parametric Study for NASP Engine Applications Using the SHIP Code, *5th National Aero-Space Plane Technology Symposium*, Paper No. 40.

Banken, G.J., Roberts, D.W., Holcomb, J.E. and Birch, S.F., 1985. An Investigation of Film Cooling on a Hypersonic Vehicle Using a PNS Flow Analysis Code, AIAA 85-1591.

Bergeles, G., Gosman, A.D. and Launder, B.E., 1980. Double-Row Discrete-Hole Cooling: an Experimental and Numerical Study, *ASME Journal of Engineering for Power*, **102**, 498–503;

also 1978, *ASME Gas Turbine Heat Transfer 1978*, V.L. Eriksen and H.L. Julien (eds.), pp. 1–7.

Bergeles, G., Gosman, A.D. and Launder, B.E., 1981. The Prediction of Three-Dimensional Discrete-Hole Cooling Processes – Part 2: Turbulent Flow, *ASME Journal of Heat Transfer*, **103**, pp. 141–145.

Brandeis, J., 1983. Influence of Finite Slot Size on Boundary Layer with Suction or Injection, *AIAA Journal*, **21**(4), pp. 636–637.

Demuren, A.O., 1983. Numerical Calculations of Steady Three-Dimensional Turbulent Jets in Cross Flow, *Computer Methods in Applied Mechanics and Engineering*, **37**, 309–328; also 1982, University of Karlsruhe, Institute for Thermal Turbomachinery, Special Research No. 80, Report No. SFB 80/T/129.

Demuren, A.O. and Rodi, W., 1983. Three-Dimensional Calculation of Film Cooling by a Row of Jets, *Notes in Numerical Fluid Mechanics, Proceedings of the Fifth GAAM-Conference on Numerical Methods in Fluid Mechanics*, Vol. 7, Friedr. Vieweg & Sohn, M. Pandolfi and R. Piva (eds.), pp. 49–56.

Demuren, A.O., 1986. Modeling Turbulent Jets in Crossflow, *Dynamics of Single-Fluid Flows and Mixing, Encyclopedia of Fluid Mechanics*, Vol. 2, Gulf Publishing Co., N.P. Cheremisinoff (ed.), pp. 430–465.

Demuren, A.O., Rodi, W. and Schonung, B., 1986. Systematic Study of Film Cooling with a Three-Dimensional Calculation Procedure, *ASME Journal of Turbomachinery*, **108**, pp. 124–130.

Dibelius, G. and Wen, B., 1989. Numerical Approximation of Film Cooling with a Three-Dimensional Calculation Procedure, *Finite Approximations in Fluid Mechanics II, Notes on Numerical Fluid Mechanics*, Vol. 25, Friedr. Vieweg & Sohn/Ballen Books, E. H. Hirschel (ed.), pp. 65–79.

El-Hadik, A.A.B., 1980. An Investigation of Flow and Heat Transfer Around the Leading Edge of a Film-Cooled Gas Turbine Blade, Ph.D. Thesis, University of Liverpool.

- El-Hadik, A.A.B. and Barrow, H., 1981. A Theoretical and Experimental Investigation of Flow and Heat Transfer in Film Cooling, *Proceedings of 2nd International Conference on Numerical Methods in Thermal Problems*, Vol. 2, Pineridge Press, pp. 1246–1256.
- El-Hadik, A.A., Awad, M.M. and Araj, F.F., 1983. A Numerical Solution for Turbulent Flow Around the Leading Edge of a Film Cooled Gas Turbine Blade, *Proceedings of ASME-JSME Thermal Engineering Joint Conference*, Vol. 4, Y. Mori and W.-J. Yang (eds.), pp. 199–204.
- Gibeling, H.J., Kreskovsky, J.P., Briley, W.R. and McDonald, H., 1981. Computation of Discrete Hole Film Cooling Flow Using the Navier–Stokes Equations, AFOSR-TR-81-0606.
- Gibeling, H.J., Shamroth, S.J., and McDonald, H., 1982. Computation of Discrete Slanted Hole Film Cooling Flow Using the Navier–Stokes Equations, AFOSR-TR-82-1004.
- Gibeling, H.J., Briley, W.R., Kreskovsky, J.P., Shamroth, S.J. and McDonald, H., 1983. Computation of Discrete Slanted Hole Film Cooling Flow Using the Navier–Stokes Equations, AFOSR-TR-83-1288.
- Jubran, B.A., 1989. Correlation and Prediction of Film Cooling from Two Rows of Holes, *ASME Journal of Turbomachinery*, **111**, pp. 502–509.
- Kohler, J. and Beer, H., 1985. Calculation of the Disturbance to Combustion Chamber Film Cooling Due to Air Injection through a Row of Jets, *Zeitschrift für Flugwissenschaften und Weltraumforschung (Journal of Aeronautics and Astronautics Research)*, **9** (Jan.–Feb.), pp. 34–42.
- Kreskovsky, J.P., Briley, W.R. and McDonald, H., 1980. Computation of Discrete Hole Film Cooling Flow Using the Navier–Stokes Equations, AFOSR-TR-80-0687.
- Launder, B.E., 1982. Modelling of Turbulent Flow in Gas-Turbine Blading: Achievements and Prospects, *International Journal of Heat and Fluid Flow*, **3**(4), pp. 171–184.
- Ljuboja, M. and Rodi, W., 1980. Calculation of Turbulent Wall Jets with an Algebraic Reynolds Stress Model, *ASME Journal of Fluids Engineering*, **102**, pp. 350–356.
- Mehta, J.M. and Burrus, D.L., 1987. A Numerical Method to Predict Gas Turbine Combustor Film-Slot Cooling Effectiveness, *Proceedings of the 8th International Symposium on Air Breathing Engines (ISABE)*, AIAA Publications, F.S. Billig (ed.), ISABE 87-7072, pp. 710–717.
- Pishardy, J.C. and Pai, B.R., 1985. Prediction of Film Cooling in the Presence of Chemical Reaction, *Proceedings of the 8th National Heat and Mass Transfer Conference*, Oxford & IBH Publishing Co., Indian Society for Heat and Mass Transfer, HMT-A21-85, pp. 11–15.
- Rodi, W. and Srivatsa, S.K., 1980. A Locally Elliptic Calculation Procedure for Three-Dimensional Flows and Its Application to a Jet in a Cross-Flow, *Computer Methods in Applied Mechanics and Engineering*, **23**, pp. 67–83.
- Scherer, V. and Wittig, S., 1989. The Influence of the Recirculating Region: A Comparison of the Convective Heat Transfer Downstream of a Backward-Facing Step and Behind a Jet in a Cross Flow, ASME 89-GT-59.
- Scherer, V., 1989. Convective Heat Transfer in Flow Separation Zones: Possibilities and Limits of an Application of Wall Function in Step and Mixing Air Flow, Ph.D. Thesis, University of Karlsruhe (in German).
- Sinitsin, D.M., 1988. A Numerical and Experimental Study of Flow and Heat Transfer from a Flush Inclined Film Cooling Slot, M.S. Thesis, University of British Columbia.
- Sinitsin, D., Djilali, N., Gartshore, I. and Salcudean, M., 1989. Film Cooling of Turbine Blades: Two Dimensional Experiments and Numerical Simulations, *Proceedings of the 36th Annual General Meeting of the Canadian Aeronautics and Space Institute*, Report No. 35.

White, A.J., 1980. The Prediction of the Flow and Heat Transfer in the Vicinity of a Crossflow, ASME 80-WA/HT-26.

Xu, J. and Ko, S.-Y., 1983. Numerical Computation for Film Cooling over a Curved Surface with Coolant Injection through Discrete Holes, *Journal of Engineering Thermophysics*, **4**(1) (in Chinese).

Yang, R.J., Weinberg, B.C., Shamroth, S.J. and McDonald, H., 1985. Turbine Vane External Heat Transfer – Volume II: Numerical Solutions of the Navier–Stokes Equations for Two- and Three-Dimensional Turbine Cascades with Heat Transfer, NASA CR-174828.

1990–1996

Abhari, R.S., 1996. Impact of Rotor–Stator Interaction on Turbine Blade Film Cooling, *ASME Journal of Turbomachinery*, **118**, pp. 123–133.

Ajersch, P., Zhou, J.-M., Ketler, S., Saleudean, M. and Gartshore, I.S., 1995. Multiple Jets in a Crossflow: Detailed Measurements and Numerical Simulations, ASME 95-GT-9.

Amer, A.A., Jubran, B.A. and Hamdan, M.A., 1992. Comparison of Different Two-Equation Turbulence Models for Prediction of Film Cooling from Two Rows of Holes, *Numerical Heat Transfer – Part A: Applications*, **21**, pp. 143–162.

Anderson, P.G., Chen, Y.S. and Farmer, R.C., 1992. Heat Transfer in Rocket Engine Combustion Chambers and Nozzles, *10th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion*, NASA Goddard Space Flight Center, Part 2, pp. 863–896.

Anderson, P.G., Cheng, G.C. and Farmer, R.C., 1993. Heat Transfer in Rocket Engine Combustion Chambers and Nozzles, *11th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion*, NASA Marshall Space Flight Center, pp. 963–990.

Anderson, P., Cheng, G. and Farmer, R., 1993. Heat Transfer in Rocket Combustion Chambers, NASA Propulsion Engineering Research Center, Pennsylvania State University, Vol. 2, Nov., pp. 111–114.

Andrews, G.E., Al Dabagh, A.M., Asere, A.A., Bazdidi-Tehrani, F., Mkpadi, M.C. and Nazari, A., 1993. Impingement/Effusion Cooling, *Heat Transfer and Cooling in Gas Turbines*, AGARD-CP-527, Paper No. 30.

Baldauf, S. and Scheurlen, M., 1996. CFD Based Sensitivity Study of Flow Parameters for Engine Like Film Cooling Conditions, ASME 96-GT-310.

Bassi, F., Rebay, S., Savini, M., Colantuoni, S. and Santoriello, G., 1993. A Navier–Stokes Solver with Different Turbulence Models Applied to Film-Cooled Turbine Cascades, *Heat Transfer and Cooling in Gas Turbines*, AGARD-CP-527, Paper No. 41.

Beeck, A., 1992. Flow Field Investigations into the Aerodynamic Behavior of a Highly Loaded Turbine Cascade with Cooling Air Injection at the Leading Edge, Ph.D. Thesis, University of the Federal Armed Forces, Munich (in German).

Beeck, A., Fottner, L., Benz, E. and Wittig, S., 1993. The Aerodynamic Effect of Coolant Ejection in the Leading Edge Region of a Film-Cooled Turbine Blade, *Heat Transfer and Cooling in Gas Turbines*, AGARD-CP-527, Paper No. 35.

Befrui, B.A., 1994. Turbulence Modeling Needs of Commercial CFD Codes: Complex Flows in the Aerospace and Automotive Industries, *Industry-Wide Workshop on Computational Turbulence Modeling*, NASA CP-10165, pp. 171–192.

Benz, E. and Wittig, S., 1992. Prediction of the Interaction of Coolant Ejection with the Main Stream at the Leading Edge of a Turbine Blade: Attached Grid Application, *Proceedings of the International Symposium Heat Transfer in Turbomachinery*, Athens.

Benz, E., Wittig, S., Beeck, A. and Fottner, L., 1993. Analysis of Cooling Jets near the Leading Edge of Turbine Blades, *Computational and*

- Experimental Assessment of Jets in Cross Flow*, 72nd Fluid Dynamics Panel Meeting and Symposium, AGARD-CP-534, Paper No. 37.
- Benz, E., 1994. Development and Extension of Fundamental Approaches for the Numerical Calculation of Turbulent Sub- and Supersonic Flows in Gas Turbines, Ph.D. Thesis, University of Karlsruhe (in German).
- Berhe, M.K. and Patankar, S.V., 1996. A Numerical Study of Discrete-Hole Film Cooling, ASME 96-WA/HT-8.
- Bernard, J., 1994. Detailed Prediction of 3D Flow and Heat Transfer on High Pressure Turbine Aerofoils: Part 2 – Detailed Prediction of Heat Transfer on Film-Cooled HP Guide Vanes, *Numerical Methods for Flow Calculation in Turbomachines*, von Karman Institute for Fluid Dynamics, Lecture Series 1994-06.
- Bittlinger, G., 1995. Tangential Slot Film Cooling: Experimental and Numerical Approaches for the Optimization of Combustor Cooling Air Requirements, Ph.D. Thesis, University of Karlsruhe (in German).
- Bohn, D. and Bonhoff, B., 1992. A Numerical Contribution to the Computation of Film Cooling Near a Diabatic Wall, Institute for Steam and Gas Turbines, RWTH, Seminar Paper (in German).
- Bohn, D. and Bonhoff, B., 1994. Computational Film Cooling Effects of a Transonic Through-Flow Turbine Nozzle with Diabatic Walls, VDI Berichte No. 1109 (in German).
- Bohn, D., Bonhoff, B., Schonenborn, H. and Wilhelmi, H., 1995. Validation of a Numerical Model for the Coupled Simulation of Fluid Flow and Diabatic Walls with Application to Film-cooled Gas Turbine Blades, *Turbomachinery – Fluid Dynamic and Thermodynamic Aspects*, *Proceedings of the 1st European Conference*, VDI Berichte No. 1186, Paper No. B-16, pp. 259–272.
- Bohn, D., Schonenborn, H., Bonhoff, B. and Wilhelmi, H., 1995. Prediction of the Film-Cooling Effectiveness in Gas Turbine Blades Using a Numerical Model for the Coupled Simulation for Fluid Flow and Diabatic Walls, *Proceedings of the 12th International Symposium on Air Breathing Engines (ISABE)*, Vol. 2, AIAA Publications, F.S. Billig (ed.), ISABE 95-7105, pp. 1150–1159.
- Bohn, D. and Runger, A., 1996. Influence of Rotor/Stator-Interaction on Film Cooling at the Rotor Leading Edge, Technische Hochschule at Aachen, ETDE-DE-464 (in German).
- Bohn, D., Kusterer, K. and Schonenborn, H., 1996. 3-D Numerical Simulation of a Film-Cooled and Convection-Cooled Turbine Blade with Non-Adiabatic Walls, *ISFMFE – Conference*, Beijing.
- Bohn, D. and Becker, V., 1996. Experimental and Numerical Investigations of the Flow Field at the Leading Edge of a Film-Cooled Turbine Guide Vane, *ISFMFE – Conference*, Beijing.
- Bohn, D., Kusterer, K. and Schonenborn, H., 1996. 3-D Numerical Simulation of the Flow through a Turbine Blade Cascade with Cooling Injection at the Leading Edge, ASME 96-GT-150.
- Bohn, D.E., Becker, V.J. and Rungen, A.U., 1996. Analysis of the Location of the Stagnation Line on a Turbine Guide Vane with Shower-Head Cooling: Experimental and Theoretical Investigations, *Proceedings of the International Congress on Fluid Dynamics and Propulsion*, pp. 127–136, Cairo.
- Butkiewicz, J.J., 1995. Development of a Novel Computational Methodology for Complex Flow Problems; Normal Slot-Jet in Crossflow, M.S. Thesis, Clemson University.
- Butkiewicz, J.J., Walters, D.K., McGovern, K.T. and Leylek, J.H., 1995. A Systematic Computational Methodology Applied to a Jet-In-Crossflow – Part 1: Structured Grid Approach, ASME 95-WA/HT-52.
- Carcasci, C., Facchini, B. and Corradini, U., 1994. A Numerical Procedure to Determine Blade Temperature of Cooled Stator Blades in Gas Turbines: A Numerical and Experimental Comparison, *Proceedings of ASME-IGTI Cogen Turbo Power '94 Conference*, Paper No. TF-08.

- Chamberlain, R., 1992. Computation of Film Cooling Characteristics in Hypersonic Flow, AIAA 92-0657.
- Chanez, P., Petot, B. and Jourden, C., 1993. Viscous Analysis of High Pressure Inlet Guide-Vane Flow Including Cooling Injections, AIAA 93-1798.
- Chen, Y.S. and Cheng, G.C., 1991. CFD Modeling of Film Cooling Test Cases, *Combustion Devices Technical Team Meeting*, NASA-MSFC.
- Chen, Y.S., Cheng, G.C. and Farmer, R.C., 1992. Reacting and Non-Reacting Flow Simulation for Film Cooling in 2-D Supersonic Flows, AIAA 92-3602.
- Chen, Y.S., Chen, C.P. and Wei, H., 1992. Numerical Analysis of Hypersonic Turbulent Film Cooling Flows, AIAA 92-2767.
- Chen, Y.S., Shang, H.M., Liao, P., Cheng, G.C., Farmer, R.C. and Chen, C.P., 1993. Numerical Simulation of Film Cooling Effectiveness in a Combustion Chamber, *Proceedings of the Pacific International Conference on Aerospace Science and Technology - 1993*, Vol. 3, pp. 1258-1265, Taiwan.
- Choi, D., 1993. A Navier-Stokes Analysis of Film Cooling in a Turbine Blade, AIAA 93-0158.
- Collins, F.G., Jechura, M., Nichols, R.H., Tramel, R., Cooper, K. and Abel, R., 1992. Advanced High Area Ratio Nozzles, *Proceedings of the CSTAR 3rd Annual Technical Symposium*, Center for Space Transportation and Applied Research (CSTAR).
- Collins, F.G., Jechura, M., Nichols, R.H., Tramel, R., Cooper, K. and Abel, R., 1992. Advanced Nozzle Concepts, *Proceedings of the CSTAR 4th Annual Technical Symposium*, Center for Space Transportation and Applied Research (CSTAR).
- Demuren, A.O., 1993. Characteristics of Three-Dimensional Turbulent Jets in Crossflow, *International Journal of Engineering Science*, **31**(6), pp. 899-913.
- Dibelius, G.H., Pitt, R. and Wen, B., 1990. Numerical Prediction of Film Cooling Effectiveness and the Associated Aerodynamic Losses with a Three-Dimensional Calculation Procedure, ASME 90-GT-226.
- Dorney, D.J., Davis, R.L. and Edwards, D.E., 1992. Investigation of Hot Streak Migration and Film Cooling Effects on Heat Transfer in Rotor/Stator Interacting Flows, United Technologies Research Center, Report 91-29-Report 1.
- Dorney, D.J. and Davis, R.L., 1993. Numerical Simulation of Turbine 'Hot Spot' Alleviation Using Film Cooling, *AIAA Journal of Propulsion and Power*, **9**(3), pp. 329-336.
- Ebrahimi, H.B. and Gilbertson, M., 1992. Two and Three Dimensional Parabolized Navier-Stokes Code for Scramjet Combustor, Nozzle and Film Cooling Analysis, AIAA 92-0391.
- Elfert, M., 1995. Film Cooling of Turbine Blade Leading Edge, Deutsche Forschungsanstalt fuer Luft- und Raumfahrt e.V. (DLR), Institute fuer Antriebstechnik, Koeln (DE), HTGT-Turbotherm, Stage 2. Subproject 2.1.8.1 A and B, Final Report (in German).
- Findlay, M.J., He, P., Salcudean, M. and Gartshore, I.S., 1996. A Row of Streamwise-Inclined Jets in Crossflow: Measurements and Calculations, ASME 96-GT-167.
- Fougeres, J.-M., Kulisa, P., Vullierme, J.-J. and Bousgarbies, J.-L., 1993. Turbine Blade Film Cooling: Model and Experimental Validation, *Revue Scientifique Snecma*, No. 4, June, pp. 53-64.
- Fougeres, J.M. and Heider, R., 1994. Three-Dimensional Navier-Stokes Prediction of Heat Transfer with Film Cooling, ASME 94-GT-14.
- Fukuyama, Y., Otomo, F., Sata, M., Kobayashi, Y. and Matsuzaki, H., 1994. Numerical Simulation of Gas Turbine Vane Film Effectiveness by Using $k-\epsilon$ Model of Turbulence, *Fall Annual Conference*, Gas Turbine Society of Japan (in Japanese).
- Fukuyama, Y., Otomo, F., Sato, M., Kobayashi, Y. and Matsuzaki, H., 1995. Prediction of Vane Surface Film Cooling Effectiveness Using Compressible Navier-Stokes Procedure and $k-\epsilon$ Turbulence Model with Wall Function, ASME 95-GT-25.

- Garg, V.K., 1992. Film-Cooled Turbine Vane Heat Transfer, *Proceedings of IMACS-International Symposium on Scientific Computing and Mathematical Modeling*, International Journal Services Inc., S.K. Dey and E.J. Kansa (eds.), pp. 245–271, Bangalore.
- Garg, V.K. and Gaugler, R.E., 1993. Heat Transfer in Film Cooled Turbine Blades, ASME 93-GT-81.
- Garg, V.K. and Gaugler, R.E., 1994. Prediction of Film Cooling on Gas Turbine Airfoils, ASME 94-GT-16; also NASA TM-106653.
- Garg, V.K., 1995. Effect of Blade Rotation on Film Cooling of Turbine Blades, *Heat and Mass Transfer 95, Proceedings of the 2nd ISHMT-ASME Heat and Mass Transfer Conference and 13th National Heat and Mass Transfer Conference*, Tata McGraw-Hill Publishing Co. Lt., New Delhi, S.S. Murthy and Y. Jaluria (eds.), India, pp. 595–600.
- Garg, V.K. and Gaugler, R.E., 1995. Effect of Velocity and Temperature Distribution at the Hole Exit on Film Cooling of Turbine Blades, ASME 95-GT-2; also NASA TM-106954.
- Garg, V.K. and Gaugler, R.E., 1995. Effect of Coolant Temperature and Mass Flow on Film Cooling of Turbine Blades, ASME 95-WA/HT-1.
- Garg, V.K. and Gaugler, R.E., 1996. Leading Edge Film Cooling Effects on Turbine Blade Heat Transfer, *Numerical Heat Transfer Part A: Applications*, **30**(2), August, 165–187; also 1995, ASME 95-GT-275 (condensed version) and NASA TM-106955.
- Garg, V.K., 1996. Adiabatic Effectiveness and Heat Transfer Coefficient on a Film-Cooled Rotating Blade, ASME 96-GT-221.
- Garg, V.K. and Abhari, R.S., 1996. Comparison of Predicted and Experimental Nusselt Number for a Film-Cooled Rotating Blade, ASME 96-GT-223.
- Garrett, J.L., 1992. Application of Computational Fluid Dynamics to the Design of the Film Cooled STME Subscale Nozzle for the National Launch System, *10th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion*, NASA Goddard Space Flight Center, Part 2, pp. 897–922.
- Gartshore, I., Salcudean, M. and Matys, P., 1991. Film Cooling Effectiveness, *Transaction of the Canadian Society of Mechanical Engineering*, **15**(1), pp. 43–55.
- Gartshore, I., Salcudean, M., Riaha, A. and Djilali, N., 1991. Measured and Calculated Values of Discharge Coefficients from Flush-Inclined Holes – Application to the Film Cooling of Turbine Blades, *Canadian Aeronautics and Space Journal*, **37**(1), pp. 9–15.
- Goldstein, R.J., Eckert, E.R.G., Patankar, S.V. and Simon, T.W., 1996. Experimental and Computational Studies of Film Cooling with Compound Angle Injection, *1995 Advanced Turbine System (ATS) Annual Review*, South Carolina Energy Research and Development Center, Report No. DOE/MC/29061-96/C0668CONF-9510109-35.
- Granser, D. and Schulenberg, T., 1990. Prediction and Measurement of Film Cooling Effectiveness for a First-Stage Turbine Vane Shroud, ASME 90-GT-95.
- Haire, S.L., 1993. Methodology for CFD Design Analysis of National Launch System Nozzle Manifold, *11th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion*, NASA Marshall Space Flight Center, Part 1, pp. 503–523.
- Hall, E.J., Topp, D.A., Heidegger, N.J. and Delaney, R.A., 1994. Investigation of Advanced Counterrotation Blade Configuration Concepts for High Speed Turboprop Systems – Task 8: Cooling Flow/Heat Transfer Analysis, NASA CR-195359.
- Hall, E.J., Topp, D.A. and Delaney, R.A., 1994. Aerodynamic/Heat Transfer Analysis of Discrete Site Film-Cooled Turbine Airfoils, AIAA 94-3070.
- He, P., Salcudean, M. and Gartshore, I.S., 1995. Computations of Film Cooling for the Leading Edge Region of a Turbine Blade Model, ASME 95-GT-20.
- He, P., 1996. Numerical Simulation of Film Cooling of a Turbine Blade Using Block-Structured

- Curvilinear Grids, Ph.D. Thesis, University of British Columbia.
- He, P., Licu, D., Salcudean, M. and Gartshore, I.S., 1996. Leading Edge Film Cooling: Computations and Experiments Including Density Effects, ASME 96-GT-176.
- Heidmann, J.D., 1995. A Numerical Study of the Effect of Wake Passing on Turbine Blade Film Cooling, AIAA 95-3044; also NASA TM-107077.
- Heidmann, J.D., 1996. The Effect of Wake Passing on Turbine Blade Film Cooling, Ph.D. Thesis, Case Western Reserve University; also NASA TM-107380.
- Hyams, D.G., 1996. A Computational Investigation of 3-D Shaped Hole Film Cooling Physics, M.S. Thesis, Clemson University.
- Hyams, D.G., McGovern, K.T. and Leylek, J.H., 1996. Effects of Geometry on Slot-Jet Film Cooling Performance, ASME 96-GT-187.
- Irmisch, S., 1995. Simultaneous Calculation of the Coolant- and Mainstream Flows Using Unstructured Meshes, Stuttgart University, Institute fuer Luftfahrtantriebe, *Turbotech Subproject 1.2.1.5*, Final Report, ETDE-DE-298 (in German).
- Irmisch, S., 1995. Simulation of Film-Cooling Aerodynamics with a 2D Navier–Stokes Solver Using Unstructured Meshes, ASME 95-GT-24.
- Jansson, L.S., Davidson, L. and Olsson, E., 1994. Calculation of Steady and Unsteady Flows in a Film-Cooling Arrangement Using a Two-Layer Algebraic Stress Model, *Numerical Heat Transfer – Part A: Applications*, **25**, pp. 237–258.
- Jansson, L.S. and Davidson, L., 1994. Numerical Simulation of Inclined Jets in a Crossflow Using a Reynolds Stress Model, *Computational Fluid Dynamics '94, Proceedings of the 2nd European Computational Fluid Dynamics Conference*.
- Kacynski, K.J. and Hoffman, J.D., 1994. The Prediction of Nozzle Performance and Heat Transfer in Hydrogen/Oxygen Rocket Engines with Transpiration Cooling, Film Cooling, and High Area Ratio, AIAA 94-2757; also NASA TM-106617, and 1993, *Proceedings of the Joint JANNAF Propulsion Meeting*, Vol. 2, pp. 181–201.
- Kamath, P., Baker, N. and McClinton, C., 1990. A Computational Design Tool for Scramjet Combustor Film Cooling and Fuel Mixing Predictions, AIAA 90-0645.
- Kamath, P.S., Holden, M.S. and McClinton, C.R., 1990. Experimental and Computational Study of the Effect of Shocks on Film Cooling Effectiveness in Scramjet Combustors, AIAA 90-1713.
- Karr, G.R., 1993. FDNS Code to Predict Wall Heat Fluxes or Wall Temperatures in Rocket Nozzles, NASA CR-196925.
- Kim, S.-W. and Benson, T.J., 1992. Fluid Flow of a Row of Jets in Crossflow – A Numerical Study, AIAA 92-0534.
- Kimura, T. and Kanda, T., 1995. Numerical Experiment on Film Cooling in Supersonic Flow, *Computational Fluid Dynamics in Aeropropulsion*, W. Ng (ed.), ASME AD-Vol. 49, pp. 169–175.
- Kimura, T. and Kanda, T., 1996. Numerical Simulation on Film Cooling in Supersonic Flow, *Proceedings of the 13th National Aerospace Lab Symposium on Aircraft Computational Aerodynamics*, pp. 69–74 (in Japanese).
- Kulisa, P., Leboeuf, F. and Perrin, G., 1992. Computation of a Wall Boundary Layer with Discrete Jet Injections, *ASME Journal of Turbomachinery*, **114**, pp. 756–764.
- Kuo, S.-L., 1995. Transport Phenomena in Subsonic and Supersonic Flows in a Duct with Mass Injection, Ph.D. Thesis, University of Michigan.
- Kurotaki, T., Nakamura, Y., Kurosaki, R., Katayama, M. and Aso, S., 1995. Numerical Simulation of Film Cooling Effect Around Axisymmetric Body in Hypersonic Flow Field, National Aerospace Laboratory, Special Publication, pp. 165–170 (in Japanese).
- Landrum, D.B. and Beard, R.M., 1996. Numerical Simulation of Film-Cooled Ablative Rocket Nozzles, NASA CR-201490; also The University of Alabama at Huntsville, Propulsion Research Center, TR-96-002.
- Langowsky, C. and Vogel, D.T., 1995. The Influence of Film Cooling on the Secondary Flow

- in a Turbine Stator – An Experimental and Numerical Investigation, AIAA 95-3040.
- Lapworth, B.L., Rose, M.G. and Nedar, R.G.D., 1996. Calculation of Flow and Heat Transfer near the Entrance to Film-Cooling Holes Using Three-Dimensional Mesh Embedding with Solution Adaptation, *International Journal of Heat and Fluid Flow*, **17**(2), pp. 155–166.
- Leboeuf, F. and Huang, G.P., 1990. The Computation of Three-Dimensional Jets, 1st ISÁIF, Beijing.
- Leboeuf, F. and Huang, G.-P., Kulisa, P. and Perrin, G., 1991. Model and Computation of Discrete Jets in Crossflow, *European Journal of Mechanics, B/Fluids*, Vol. 10, No. 6, pp. 629–650.
- Leboeuf, F. and Sgarzi, O., 1995. Film Cooling in Turbines: A Review of the Behavior of Discrete Three-Dimensional Jets, *Special Symposium on Recent Advances in Turbomachinery*, Pennsylvania State University (to appear in *Turbomachinery Fluid Dynamics and Heat Transfer*, Marcel Dekker Inc., Mechanical Engineering Series/110, C. Hah (ed.), 1997).
- Leylek, J.H. and Zerkle, R.D., 1994. Discrete-Jet Film Cooling: A Comparison of Computational Results with Experiments, *ASME Journal of Turbomachinery*, **116**, pp. 358–368.
- Liu, J.S., Utz, R. and Bozzola, R., 1994. Aerodynamic Design and Analysis of a Gas Producer Turbine Stator with Film Cooling Injection, AIAA 94-2928.
- Martelli, F., Michelassi, V. and Boretti, A.A., 1992. Numerical Modeling of Coolant Jet Flow in Turbine Cascades, *Journal of French Mechanics*, No. 4.
- Martelli, F. and Michelassi, V., 1993. Studies on Coolant Problems in Aeronautical Turbine Cascades, *Proceedings of the 11th International Symposium on Air Breathing Engines (ISABE)*, Vol. 2, AIAA Publications, F.S. Billig (ed.), ISABE 93-7074, pp. 757–765.
- Matesanz, A., Velazquez, A. and Rodriguez, M., 1993. Numerical Simulation of Slot Film Cooling in Convergent-Divergent Nozzles, AIAA 93-1977.
- McConnaughey, P.K., Garcia, R., Griffin, L.W. and Ruf, J.H., 1993. Computational Fluid Dynamics (CFD) Applications in Rocket Propulsion Analysis and Design, NASA Propulsion Engineering Research Center, Pennsylvania State University, Vol. 2, Nov., pp. 125–129.
- Mekkes, G.L., 1993. Computational Analysis of Hypersonic Shock Wave/Wall Jet Interaction, AIAA 93-0604.
- Merkle, C.L., 1996. NASA Flow Fields Analysis, NASA CR-201532.
- Michelassi V., Martelli, F. and Amecke, J., 1994. Aerodynamic Performance of a Transonic Turbine Guide Vane with Trailing Edge Coolant Ejection – Part II: Numerical Approach, ASME 94-GT-248.
- Natalini, G. and Sciubba, E., 1994. Entropy Generation Rates in Air-Cooled Gas Turbine Nozzles: A Numerical Configuration Study, *Proceedings of the ASME-IGTI Cogen Turbo Power '94 Conference*, Paper No. TF-18.
- O'Connor, J.P., 1991. A Numerical Study of Film Cooling in Supersonic Flow, M.S. Thesis, University of Texas at Arlington.
- O'Connor, J.P. and Haji-Sheikh, A., 1992. Numerical Study of Film Cooling in Supersonic Flow, *AIAA Journal*, **30**(10), pp. 2426–2433.
- Osakabe, M., Miyazawa, T., Motoda, T. and Wu, Y.W., 1995. Film Cooling Behavior in Thin Rectangular Channel – Quick Prediction with k -epsilon Turbulent Model, *Proceedings of the Yokohama International Gas Turbine Congress*, Vol. 2, Gas Turbine Society of Japan, pp. 233–238.
- Pitalo, G.A. and Kolibal, J., 1996. Numerical Modeling of Altitude Diffusers, AIAA 96-2280.
- Rexroth, C.-H., 1996. Methods for an Efficient Calculation of Complex Flow on Unstructured Grids, Ph.D. Thesis, University of Karlsruhe (in German).
- Roth, K.R., Fearn, R.L. and Thakur, S.S., 1992. Evaluation of a Navier–Stokes Prediction of a Jet in a Crossflow, *AIAA Journal of Aircraft*, **29**(2), pp. 185–193.

- Saabas, H.J. and Riahi, A., 1993. Numerical Simulation of Airfoil Film Cooling: A Jet in Crossflow, *Technology Requirements for Small Gas Turbines*, AGARD-CP-537, Paper No. 36.
- Salcudean, M., 1991. Computational Fluid Flow and Heat Transfer – An Engineering Tool, *Proceedings of the 13th Canadian Congress of Applied Mechanics*, pp. 38–39.
- Sarkar, S. and Bose, T.K., 1995. Comparison of Different Turbulence Models for Prediction of Slot-Film Cooling: Flow and Temperature Field, *Numerical Heat Transfer – Part B: Fundamentals*, **28**, pp. 217–238.
- Sarkar, S. and Bose, T.K., 1995. Navier–Stokes Analysis Applied to Film Cooled Turbine Cascades, *Proceedings of the 9th International Conference on Numerical Methods in Laminar and Turbulent Flow*, Pineridge Press, Vol. 9, Part 1, pp. 806–817.
- Sarkar, S. and Bose, T.K., 1996. Numerical Analysis of Slot-Film Cooling – A Parametric Study, *Journal of Aeronautical Society of India*, **48**(1), pp. 80–90.
- Sarkar, S. and Bose, T.K., 1996. Numerical Analysis of Slot-Film Cooling: Effectiveness and Flow Field, *ASME Journal of Fluids Engineering*, **118**, pp. 864–867.
- Sathyamurthy, P. and Patankar, S.V., 1990. Prediction of Film Cooling with Lateral Injection, *Heat Transfer in Turbulent Flow*, *AIAA/ASME Thermophysics and Heat Transfer Conference*, R.S. Amano *et al.* (eds.), ASME, HTD-Vol. 138, pp. 61–70.
- Sathyamurthy, P.S. and Patankar, S.V., 1992. Film Cooling Studies Using a Three-Dimensional Parabolic Procedure, University of Minnesota, Supercomputer Institute, Research Report UMSI 92/44.
- Sbresny, H., 1996. Investigation of Unstructured and Blockstructured Flow-Solvers with Regard to Numerical Simulation of Film-Cooling, Final Report, Stuttgart University, Institute fuer Luftfahrtantriebe, DE 96-758244 and ETDE-DE-352 (in German).
- Sun, Y., 1996. An Experimental and Numerical Investigation of Heat Transfer Downstream of a Normal Film Cooling Injection Slot, Ph.D. Thesis, University of British Columbia.
- Tao, Z., Ding, S., Xu, G. and Han, S., 1996. Numerical Analysis of the Conjugate Heat Transfer Process within the Tip of a Turbine Blade, *Journal of Aerospace Power*, **1**(1), 59–62 (in Chinese).
- Vogel, T., 1992. Computation of 3D-Viscous Flow and Heat Transfer for the Application to Film Cooled Gas Turbine Blades, *CFD Techniques for Propulsion Applications*, AGARD-CP-510, Paper No.7.
- Vogel, D.T., 1993. Navier–Stokes Calculation of Turbine Flows with Heat Transfer and Film Cooling, *Gas Turbines and Gas Cycle Plants, International Symposium*, Bled, Slovenia.
- Vogel, D.T., 1994. Navier–Stokes Calculation of Turbine Flows with Film Cooling, *Proceedings of the 19th Congress of the International Council of the Aeronautical Sciences*, AIAA, Vol. 2, ICAS-94-2.5.3, pp. 1572–1586, Anaheim.
- Vogel, D.T., Wilfert, G. and Fottner, L., 1995. Numerical and Experimental Investigation of Film Cooling from a Row of Holes at the Suction Side of a Highly Loaded Turbine Blade, *Proceedings of the 12th International Symposium on Air Breathing Engines (ISABE)*, Vol. 2, AIAA Publications, F.S. Billig (ed.), ISABE 95-7103, pp. 1121–1139.
- Vogel, D.T., 1995. The Interaction between Film Cooling and Secondary Flow in the Turbine Stator – Investigation of Reynolds and Turbulence-Model Influence, *6th CFD Symposium*, Lake Tahoe.
- Vogel, D.T., 1996. Navier–Stokes Simulation of the Flow Around a Leading Edge Film-Cooled Turbine Blade Including the Interior Cooling System and Comparison with Experimental Data, ASME 96-GT-71.
- Walters, D.K., McGovern, K.T., Butkiewicz, J.J. and Leylek, J.H., 1995. A Systematic Computational

- Methodology Applied to a Jet-In-Crossflow Part 2: Unstructured/Adaptive Grid Approach, ASME 95-WA/HT-2.
- Walters, D.K., 1996. A Systematic Computational Methodology for Film-Cooling Applications, M.S. Thesis, Clemson University.
- Walters, D.K. and Leylek, J.H., 1996. A Systematic Computational Methodology Applied to a Three-Dimensional Film-Cooling Flowfield, ASME 96-GT-351.
- Ward, S.C., Fricker, D.A. and Lee, R.S., 1993. Validation of a CFD Model for Predicting Film Cooling Performance, AIAA 93-2672.
- Weigand, B. and Harasgama, S.P., 1994. Computations of a Film Cooling Turbine Rotor Blade with Non-Uniform Inlet Temperature Distribution Using a Three-Dimensional Viscous Procedure, ASME 94-GT-15.
- Wen, B., 1991. Numerical Investigation of the Cooling Efficiency and Influence of Cooling Air Ejected through Rows of Cooling Holes on Gas Turbine Vanes, Ph.D. Thesis, Aachen University of Technology (in German).
- Wittig, S., Schulz, A., Gritsch, M. and Thole, K.A., 1996. Transonic Film-Cooling Investigations: Effects of Hole Shapes and Orientations, ASME 96-GT-222.
- Woodbury, K.A., 1991. Assessment of the NASA Code FDNS2D for Computation of Film Cooling Effectiveness, *Combustion Devices Technical Team Meeting*, NASA-MSFC; also Technical Report ZZ, NASA/ASEE SFFP.
- Woodbury, K.A., 1992. Analysis of Film Cooling in Rocket Nozzles, NASA CR-192003.
- Woodbury, K.A., 1993. Analysis of Film Cooling in Rocket Nozzles – Final Report, NASA CR-194674.
- Xu, J.-Z., Ko, S.-Y., Chen, S.-J. and Tsou, F.-K., 1990. Computer Simulation of Film Cooling with Coolants from One and Two Rows of Holes, ASME 90-WA/HT-7.
- Yan, W.-M. and Soong, C.-Y., 1993. Numerical Study of Liquid Film Cooling along an Inclined Plane, *Warme- und Stoffübertragung (Thermal and Fluid Dynamics)*, **28**, pp. 233–241.
- Yan, W.-M. and Soong, C.-Y., 1993. Numerical Study of Liquid Film Cooling in a Turbulent Gas Stream, *International Journal of Heat and Mass Transfer*, **36**(16), pp. 3877–3885.
- Yang, R.-J., 1996. Assessment of Turbulence and Chemistry Models for Film-Cooled Nozzle Flows, *AIAA Journal of Thermophysics and Heat Transfer*, **10**(2), pp. 284–289.
- Zerkle, R. and Prakash, C., 1994. A Summary of Computational Experience at GE Aircraft Engines for Complex Turbulent Flows in Gas Turbines, *Industry-Wide Workshop on Computational Turbulence Modeling*, NASA CP-10165, pp. 41–43.
- Zhang, M., Chen, X., Tsou, F.-K., Chen, S.-J. and Ge, S., 1990. An Investigation on Film-Cooling from Two-Staggered Rows of Holes. II – Effectiveness, *Journal of Aerospace Power*, **5**(1), pp. 6–10 (in Chinese with English Abstract).
- Zhang, X. and Collins, M.W., 1993. Flow and Heat Transfer in a Turbulent Boundary Layer through Skewed and Pitched Jets, *AIAA Journal*, **31**(9), pp. 1590–1599.
- Zhou, J.-M., 1990. A Multi-Grid Method for Computation of Film Cooling, M.S. Thesis, University of British Columbia.
- Zhou, J., 1992. Experimental and Computational Investigation of Film Cooling: 2-d Approach, University of British Columbia, Mechanical Engineering Department, Technical Report.
- Zhou, J.-M., Salcudean, M. and Gartshore, I.S., 1993. A Numerical Computation of Film Cooling Effectiveness, *Proceedings of the International Conference on Near-Wall Turbulent Flows*, Elsevier Science Publishers B.V., R.M.C. So *et al.* (eds.), pp. 377–386.
- Zhou, J.-M., Salcudean, M. and Gartshore, I.S., 1993. Prediction of Film Cooling by Discrete-Hole Injection, ASME 93-GT-75.

Zhou, J.-M., 1994. A Computational and Experimental Investigation of Gas Turbine Blade Film Cooling, Ph.D. Thesis, University of British Columbia.

Zhou, J.-M., Salcudean, M. and Gartshore, I.S., 1994. Application of the Multiple-Time-Scale Turbulence Model to the Prediction of 2-D Film Cooling Effectiveness, *Heat Transfer 1994 – Proceedings of the 10th International Heat Transfer Conference*, Vol. 3, G.F. Hewitt (ed.), Paper No. 4-EC-27, pp. 125–130.

Acknowledgment

A special thanks and appreciation is extended to Ms. Sandra Moltz of the GE Aircraft Engines Lynn library for her assistance in this research. Without the outstanding resources of the GEAE and MIT library systems, the extent of this bibliography would not have been possible.

ENERGY MATERIALS

Materials Science & Engineering for Energy Systems

Maney Publishing on behalf of the Institute of Materials, Minerals and Mining

NEW
FOR
2006

Economic and environmental factors are creating ever greater pressures for the efficient generation, transmission and use of energy. Materials developments are crucial to progress in all these areas: to innovation in design; to extending lifetime and maintenance intervals; and to successful operation in more demanding environments. Drawing together the broad community with interests in these areas, *Energy Materials* addresses materials needs in future energy generation, transmission, utilisation, conservation and storage. The journal covers thermal generation and gas turbines; renewable power (wind, wave, tidal, hydro, solar and geothermal); fuel cells (low and high temperature); materials issues relevant to biomass and biotechnology; nuclear power generation (fission and fusion); hydrogen generation and storage in the context of the 'hydrogen economy'; and the transmission and storage of the energy produced.

As well as publishing high-quality peer-reviewed research, *Energy Materials* promotes discussion of issues common to all sectors, through commissioned reviews and commentaries. The journal includes coverage of energy economics and policy, and broader social issues, since the political and legislative context influence research and investment decisions.

CALL FOR PAPERS

Contributions to the journal should be submitted online at
<http://ema.edmgr.com>

To view the Notes for Contributors please visit:
www.maney.co.uk/journals/notes/ema

Upon publication in 2006, this journal will be available via the Ingenta Connect journals service. To view free sample content online visit: www.ingentaconnect.com/content/maney

For further information please contact:

Maney Publishing UK
Tel: +44 (0)113 249 7481 Fax: +44 (0)113 248 6983 Email: subscriptions@maney.co.uk
or
Maney Publishing North America
Tel (toll free): 866 297 5154 Fax: 617 354 6875 Email: maney@maneyusa.com

EDITORS

Dr Fujio Abe
NIMS, Japan

Dr John Hald, IPL-MPT,
Technical University of
Denmark, Denmark

Dr R Viswanathan, EPRI, USA

SUBSCRIPTION INFORMATION

Volume 1 (2006), 4 issues per year
Print ISSN: 1748-9237 Online ISSN: 1748-9245
Individual rate: £76.00/US\$141.00
Institutional rate: £235.00/US\$435.00
Online-only institutional rate: £199.00/US\$367.00
For special IOM³ member rates please email
subscriptions@maney.co.uk

For further information or to subscribe online please visit
www.maney.co.uk