COMPACT TRANSPIRATION COOLING SYSTEMS

R. W. Newman and R. W. Allen

In the future, thermal protection of hypersonic flight leading edges may require active transpiration cooling systems. To meet the space restrictions placed on such systems by low drag requirements, a compact-plenum system has been proposed wherein the coolant is delivered from a storage container via small tubing to a porous channel where both radial and axial flow exist. Efficient design of such systems requires parametric studies to define the most desirable porous matrix geometry, porosity, plenum length, and flow control device. To conduct these studies, two complex computer programs were written which are capable of computing three-dimensional heat and mass flow. Evaluation of the accuracy of one of these programs was attempted by a series of free-jet tests on a cylindrical leading edge flat plate model. Various transpirant coolant flow rates were used. Measurements were recorded of transpirant mass flow rate and temperature, internal plenum pressures, and model surface temperatures. The measured steady-state values are compared with computed values.

Introduction

ALTHOUGH CONSIDERABLE RESEARCH HAS BEEN DEVOTED to experimental and analytical studies of gas-transpiration cooling, its use in thermal protection of missile leading edges is limited. Yet, porous-wall gas-transpiration cooling ultimately has promise where system reusability or surface-shape preservation are important considerations. The gas-transpiration process is more stable and controllable than liquid transpiration with vaporization. When compared to ducted cooling, gas-transpiration cooling makes more effective use of on-board coolant reserve because aerodynamic heating is partially blocked. When compared to ablation, porous-wall gas-transpiration cooling systems offer externally cooled surfaces of nondeteriorating configuration.

Up to the present time, gas-transpiration systems used in research have employed amply-sized plenum chambers coupled to coolant feeder lines of size and number sufficient to virtually preclude spatial variations in coolant pressure and temperature within the plenum chambers. However, because missile leading edge installations offer less space for plenum chambers and feeder lines, it is important to assess transpiration system performance under the influence of spatial distributions in plenum coolant pressure and temperature.

The foregoing considerations led to the concept of a compact gas-transpiration cooling system which is characterized by small coolant feeder line and small plenum. Computational procedures were developed for handling time-varying pressure and temperature distributions in coolant feeder lines, in the compact plenum, and in the porous wall. Finally, these procedures were brought together in the following two computer programs:

1. Compact Transpiration Cooling Program (CTC).
2. Three-Dimensional Transpiration Cooling Program (TDTC).

CTC can handle three-dimensional thermal analysis of in-flight transpiration system pressure, temperature, and mass flow conditions as they interact with in-flight aerodynamic heating, surface radiation, and transient heat conduction processes within flight structures. To keep the computation times of CTC within reasonable bounds, it was necessary to limit fluid flow within each porous element of the transpiration system to one direction. As a supplement to CTC, a second program (TDTC) was written to cover computation of three-dimensional heat and mass transfer in those porous sections of the compact plenum system which CTC predicts to be of critical importance. TDTC is capable of computing heat and mass transfer rates in any aerodynamically-heated three-dimensional porous section whose external surface pressure distribution is known.

For direct comparison with computed values from the CTC programs, an experimental test program was conducted to provide steady-state model temperature, pressure, and mass flow data, since no published test results were available for compact transpiration cooling systems.

This paper describes the CTC computer program, the TDTC three-dimensional flow computer program, the leading edge experiments, and a comparison of experimental and computed values.

The CTC Computer Program

A Compact Gas-Transpiration Cooling System in Flight—The compact gas-transpiration cooling system has a specific application to thermal protection of leading edges in high-speed flight. A working system, shown in elemental form in Figs. 1 and 2, utilizes a compact plenum and porous segment running along the leading edge of the flight structure. Initial thermal conditions of the flight structure are specified, and it is assumed to be launched into a particular trajectory where it is subjected to prescribed aerodynamic conditions denoted schematically by the shock wave and boundary layer in Fig. 1. Once the flight is underway, transpiration cooling gas from an on-board high-pressure reservoir (Fig. 2) is supplied through piping to the compact plenum located immediately behind the porous segment of the leading edge. Coolant flow to the compact plenum is controlled by an up-stream flow-control device located in the supply line, Fig. 2. Upon entering the compact plenum, coolant gas flows spanwise while some coolant gas transpires outward into the stagnation region. The action taking place when the transpiring coolant emerges from the external porous surface, is called "blowing." Since this coolant is moving in a direction counter-current to the inward-directed areodynamic heat load, the amount of heat reaching the surface is significantly reduced. In addition, the emerging coolant joins the external boundary layer and is swept aft over nonporous surfaces of the flight body, Fig. 1. This is called "film-cooling." Also, one can see that some coolant gas flowing spanwise in the compact plenum, Fig. 2, may be bled off at the downstream end through a downstream flow-control device. This provisional increase in total spanwise coolant flow rate in the compact plenum can reduce the spanwise variation in coolant temperature. Coolant from the downstream bleed may be utilized elsewhere in the flight body or discharged overboard.

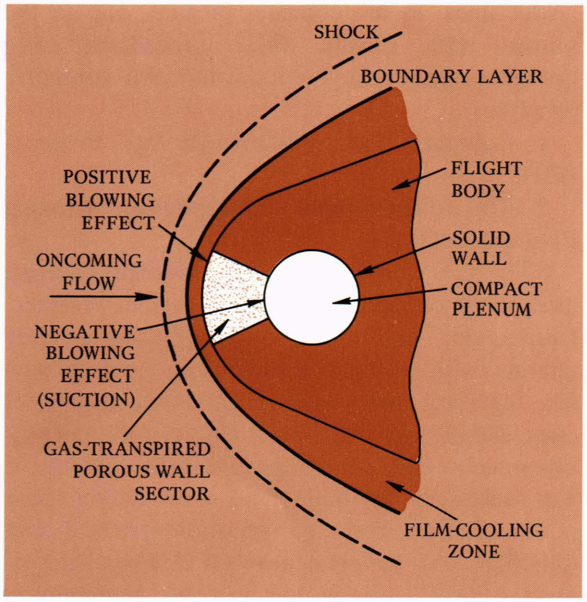

Fig. 1—Gas-transpiration cooling with a compact-plenum installation on a leading edge.

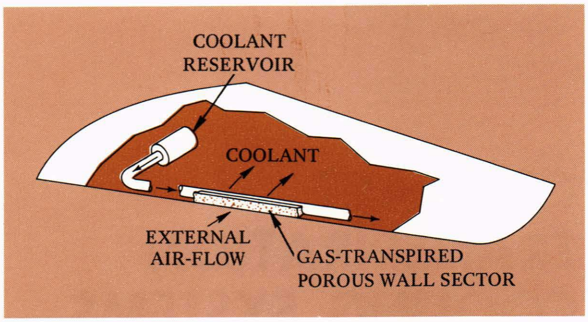

Fig. 2—Compact gas-transpiration cooling system for leading edge cooling.

Thermal Performance Assessment—As noted earlier, CTC is designed for use in assessing the thermal performance of a proposed compact plenum system. This assessment involves the determination of the coolant requirement, coolant distribution, and coolant pressures, as well as the temperature distribution in the structure as the flight progresses. For a more complete assessment, a proposed transpiration system may be subjected to a variety of anticipated flight conditions associated with the flight vehicle mission. Also, the effectiveness of different modes of coolant supply control should be evaluated. Subsequently, new designs incorporating new configurations of the leading edge, compact plenum, and associated piping may be subjected to thermal analysis, in order to find the system which performs optimally.

Capability of CTC—CTC consists of subroutines that are assembled into a MAIN program by the user. CTC subroutines are based on finite-difference numerical methods for computing coolant pressures, coolant mass flow rates, coolant temperatures, structure temperatures, and heat flow rates. Conditions to be specified by the user are (a) structural conditions, (b) cooling system conditions, and (c) initial conditions and flight conditions. When these conditions have been prescribed numerically, the program can determine the time-dependent temperatures in a three-dimensional flight structure model fitted with transpiring porous-wall segments, compact cooling-plenum passages, and coolant distribution piping. A unique feature of the program is its capability of handling finite difference calculations of the longitudinal pressure and temperature distributions in the compact plenum, and calculation of coolant discharge distribution over the external porous surface. A limitation dictated by program size and complexity is that coolant flow through the matrix of the porous wall has been programmed for one-dimensional flow along direct lines running from the compact plenum to the outside surface.

Figuratively speaking, CTC subroutines provide a set of thermal network elements. The user can specify elements of any desired physical shape, size, and material, by introducing appropriate numerical values in preparing the MAIN program. These elements can be interconnected into a network representing a thermal model of any given flight structure. The CTC coolant-flow subroutine also provides a set of elements by means of which the nature of the compact plenum and the porous matrix can be specified. These elements, known as flow elements, can be of any desired shape and size. Interconnections are specified so as to represent the compact transpiration cooling system under study and so as to thermally connect the cooling system to the structural network. CTC input flight history is user-specified in terms of (a) local flow conditions versus Mach number, (b) Mach number and altitude versus time, and (c) atmospheric properties versus altitude. Optionally, the input flight history can take the form of the aerodynamic flow conditions of a test facility. Overall, there is substantial generality in CTC. This is attributable to the range of choices in system geometry, aerodynamic flow conditions, and coolant flow conditions. Additional information on the contents and use of CTC has been given by the authors.[1]

Three-Dimensional Computer Program (TDTC)

In most high-speed leading edge applications there is a strong circumferential static pressure gradient present. This can cause significant transpirant cross-flow within the porous matrix. However, the inclusion of three-dimensional cross-flow in the CTC computer program would increase the number of calculations per time step. It would also increase the total number of time steps, since accurate prediction of three-dimensional flow usually requires that the elements be closely spaced. To prevent excessive computer run times, it appeared desirable to limit CTC to unidirectional transpirant flow within each porous element and to develop the separate TDTC program to determine any perturbations which may occur due to three-dimensional cross-flow within the porous matrix.

Capability of TDTC—The TDTC computer program predicts three-dimensional heat and mass transfer in any arbitrary-shaped porous material whose static pressure is known at all free surfaces. TDTC is similar to CTC in that it uses finite difference techniques to compute transient model temperatures. However TDTC provides additional calculations within each time step which compute the quasi-steady-state three-dimensional mass flow within the porous matrix.

TDTC consists of a set of subroutines which are assembled into a MAIN program to specify flight conditions, surface pressures, transpirant properties, material properties, elemental flow resistance coefficients, initial temperatures, and geometry. By calling the appropriate subroutines, the program first calculates pressure and trans-

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[1] R. W. Newman and R. W. Allen, *A User's Guide for a Compact Transpiration Cooling (CTC) Computer Program,* APL/JHU TG 1179, to be published.

pirant flow distributions within the porous matrix and then calculates radiation, conduction, and mass flow heating rates between elements. Other subroutines in the program compute aerodynamic heating rates to surface elements. These rates are corrected for film-cooling and transpiration blowing when appropriate and are then used to compute new element temperatures at a subsequent time.

The capability of calling subroutines as they are required for each individual application provides substantial generality to the TDTC program and allows it to be used in analyzing a variety of transpiration cooled systems other than the compact plenum system for which it was orginally written.

Transpiring Model Test Program

A free-jet test program was developed to provide experimental data for comparison with analytical values computed using CTC. Additional information on the test program has been published by Newman.[2]

The leading edge test model is shown in Fig. 3a and schematically in Fig. 3b. It is made of stainless steel and has a ½-inch-diameter leading edge of 5¼-inch span affixed to a ½-inch-thick, hollow flat plate extending 3¾ inches aft. A ⅛-inch-wide porous segment extends along the leading edge in the manner shown in Fig. 2. The compact plenum has a bore of 0.186 inch and runs along the centerline of the leading edge.

The test model instrumention is also shown in Figs. 3a and 3b. Model surface temperatures were measured at the matrix centerline (T_3, T_4, T_5),

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[2] R. W. Newman, *Compact Transpiration Cooling Free-Jet Test Results and Comparison with Theory,* APL/JHU TG 1178, Oct. 1972.

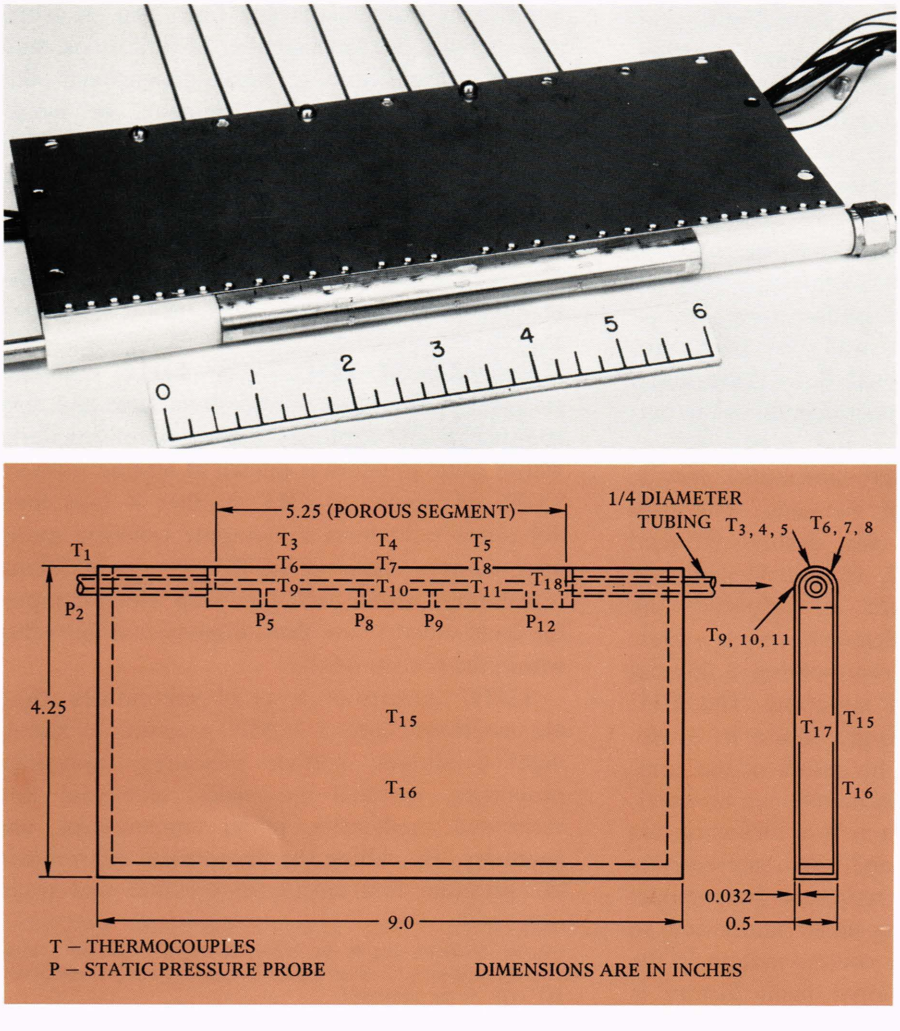


Fig. 3—(a) Porous leading edge test model; (b) Test model with temperature and pressure instrumentation.

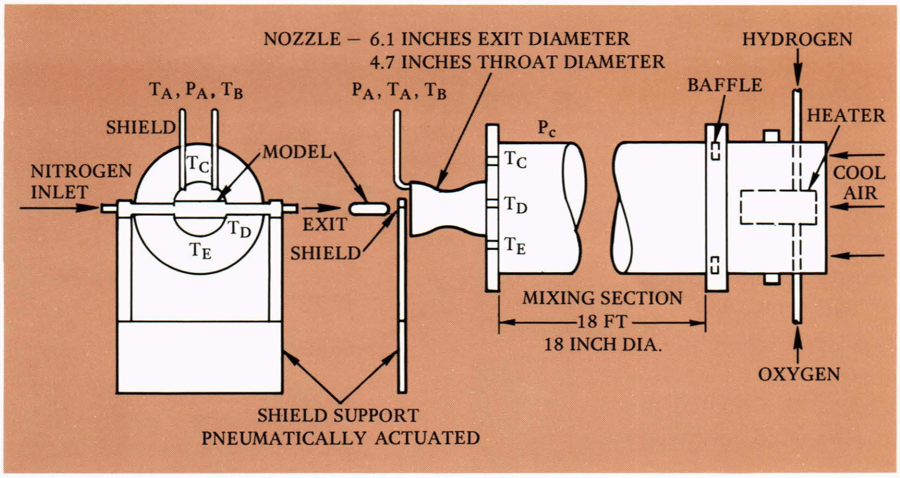


Fig. 4—Schematic of free-jet system.

aft of the centerline at 45° (T_6, T_7, T_8) and at 90° (T_9, T_{10}, T_{11}). Also measured were temperatures on the inside of the flat plate section (T_{15} and T_{16}) and the nitrogen gas temperature at the entrance and exit of the test section (T_1 and T_{18}).

Test model instrumentation included measurements of static pressure inside the compact plenum. Pressure transducer P_5 measured the absolute static pressure at the entrance of the porous plenum section. Pressure changes along the compact plenum axis were measured by three differential pressure transducers located between stations P_5 and P_8, P_9, P_{12}, respectively.

The nitrogen coolant flow system consisted of a sonic flow metering orifice placed upstream of the model to provide a constant nitrogen flow rate to the compact plenum test section. Constant nitrogen flow out of the test section was achieved via a second orifice and a pressure regulator placed at the exit of the plenum section. Water baths prior to each orifice eliminated time-dependent temperature variations in nitrogen gas entering each orifice.

Before conducting free-jet tests, it was first necessary to run several bench tests on the transpiration cooled model and its associated nitrogen flow regulating system. These tests determined the model porous matrix flow-resistance coefficients for each of five axial sections. They also determined the average inner-wall roughness coefficient, and the discharge coefficients of the flow regulating orifices.

The free-jet system consists of a hydrogen-oxygen vitiated-air heater, baffle, mixing section, and Mach 2 nozzle shown schematically in Fig. 4. A vitiated heater was chosen since it provides the cleanest air of the heaters available. This was important since any particles present in the test stream would impinge on the porous leading edge and decrease its permeability. However, even using the vitiated air heater, the airstream was not entirely free of particles.

The baffle and mixing sections were placed downstream of the heater to promote complete mixing and burning of the hydrogen-oxygen mixture. This was necessary to give a uniform temperature airstream at the entrance to the nozzle. A Mach 2 nozzle was attached directly to the mixing section and the model was supported from the nozzle. A movable shield was placed in front of the test model to reduce model heating and particle damage during start-up.

The free-jet system was instrumented as shown in Fig. 4. The total temperature of the stream was measured by total temperature probes T_A and T_B, located in the nozzle exit plane and additional probes (T_C, T_D, T_E) located upstream of the nozzle. A total-pressure probe P_A was mounted at the nozzle exit plane and a static pressure tap (P_C) was located in the mixing section.

Free Jet Test Results—Five runs were made on the transpiring leading-edge model. Each of these was conducted with nearly the same free-jet stream conditions, but with significantly different transpirant flow rates. Each test required nearly three minutes for the model temperatures to come to equilibrium. More than half of this time the shield was in front of the model while the desired steady free-jet stream conditions were being established. Temperature and pressure histories for a typical run are presented in Fig. 5. The free-stream total temperature (T_A) reached a steady-state value of 500°F at 60 seconds after rising abruptly to nearly 600°F during heater start-up. At 90 seconds, when the protective shield was removed, the model surface temperature increased as indicated. At this time, the plenum pressure also increased slowly owing to the finite time required to increase the gas density in the plenum and its associated transducer lead lines. The unexpected decrease in nitrogen gas exit temperature following shield removal and temperature increase following free-jet shut down, were also related to the density change in the associated nitrogen lines.

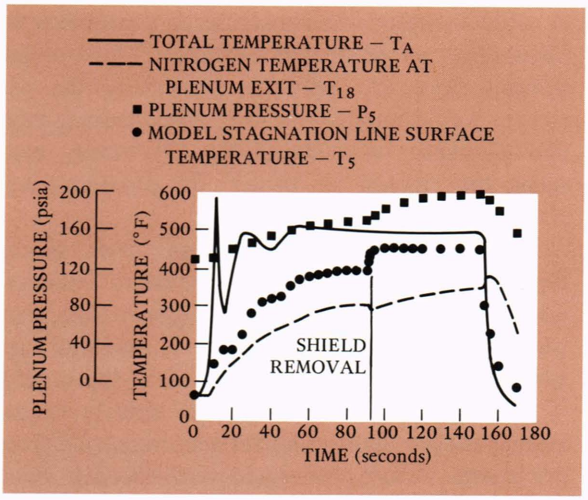
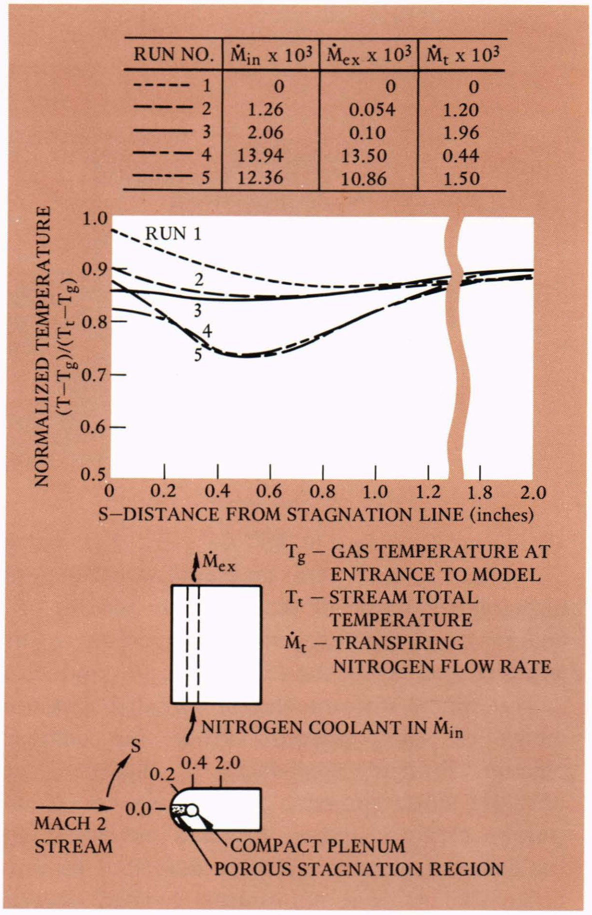


Fig. 5—Transient temperature and pressure data for free-jet run No. 2.

During testing, the main-air total temperature and inlet nitrogen gas temperatures varied somewhat from one run to the next. The variations have been removed by using these temperatures as reference values as noted on the ordinate of Fig. 6. The normalized surface temperature distributions over the model leading edge presented in Fig. 6 show Run 1 to have the highest surface temperatures at all stations, corresponding to the fact that there was no coolant flow (see Table 1). On the other hand, Runs 4 and 5 had very large axial through-flow which provided a large amount of ordinary duct-cooling effect. This is seen by the response of the nonporous outer surfaces at $S = 0.2$, $S = 0.4$, and $S = 1.0$ in Fig. 6. The importance of transpiration cooling becomes clear when Runs 4 and 5 are compared. Run 5 had less total mass flow than Run 4 and yet better cooling was provided at the stagnation line. The effectiveness of transpiration cooling is even more noticeable when Runs 3 and 4 are compared. In the critical stagnation region, Run 3 actually provided better thermal protection with less than 1/6 the mass flow of Run 4. In summary, the nonporous outer surface temperatures were dependent primarily on the amount of ordinary duct-cooling effect and the porous stagnation surface temperatures were strongly dependent on the transpiration mass flow rate. A comparison of Runs 4 and 5 shows no significant film-cooling effect.



RUN NO.	$\dot{M}_{in} \times 10^3$	$\dot{M}_{ex} \times 10^3$	$\dot{M}_t \times 10^3$
1	0	0	0
2	1.26	0.054	1.20
3	2.06	0.10	1.96
4	13.94	13.50	0.44
5	12.36	10.86	1.50

Fig. 6—Experimental normalized surface temperatures.

Comparison of Computed and Experimental Values

The primary purpose of the free-jet test program was to provide data for use in evaluating the CTC computer program. Therefore, experimental and analytical results in the following four areas were compared:

TABLE 1

TRANSPIRATION MODEL TEST CONDITIONS, EXPERIMENTAL RESULTS, AND COMPUTED RESULTS

	Nitrogen Mass Flow Conditions *(lb/s × 10⁻³)*			*Test-Jet Conditions*		*Results*	
Run	*Plenum Inlet Flow*	*Plenum Exit Flow*	*Flow Into Stagnation Region*	*Total Temp. (°F)*	*Total Pressure (psia)*	*Plenum Pressure (psia) Experimental/ Computed*	*Gas Temp. at Plenum Outlet (°F) Experimental/ Computed*
1	0.0	0.0	0.0	510	111	78/78	452/–
2	1.26	0.054	1.20	487	112	197.4/208	346/273
3	2.06	0.10	1.96	527	118	269.2/274	362/258
4	13.94	13.50	0.44	512	113	139.2/139.3	113/129
5	12.36	10.86	1.50	517	120	234.6/237	126/138

1. Surface temperature (T_3 through T_{11}, Fig. 3b).
2. Nitrogen gas temperature rise along plenum axis (T_{18}, Fig. 3b).
3. Static pressure in compact plenum (P_5, Fig. 3b).
4. Static pressure distribution along compact plenum (P_5, P_8, P_9, P_{12}, Fig. 3b).

Analytical Model—The analytical model used in the CTC computer program is shown in Fig. 7. Only half the test model was analyzed since flow conditions are symmetric for both the top and bottom halves. The analytical model is divided into six axial sections, four radial sections, and six sections in the external flow direction. The nitrogen flow rate entering and leaving the compact plenum sections are specified from measured experimental values. The CTC program uses these values and the matrix flow-resistance coefficients to compute the plenum pressure required to force the given transpirant mass flow through the porous matrix. In this calculation the nitrogen flow through the porous matrix is assumed to be unidirectional with no circumferential cross-flow within the matrix.

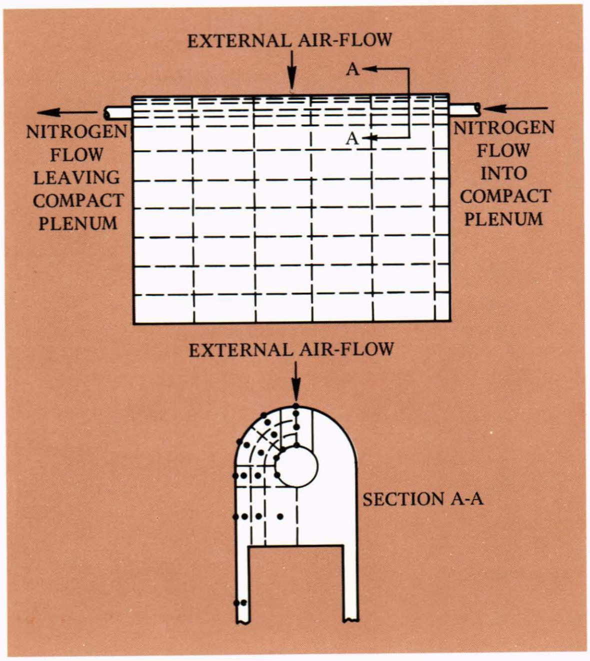


Fig. 7—Analytical model of transpiring leading edge free-jet test model.

Aerodynamic heating rates to the porous surface elements in the stagnation region were computed in CTC using the Sibulkin equation[3] and the experimentally measured stream total-temperature and total-pressure. Heat transfer coefficients for solid surface elements adjacent to the porous matrix employed the stagnation heating equation with a cos θ correction factor. Heating rates to the remaining solid surface elements were computed from flat plate theory and were reduced by radiation to room temperature assuming a surface emissivity of 0.9. CTC corrected each local heating rate for transpiration blowing or film cooling according to correction techniques that have been presented.[4,5]

Correlation of Surface Temperatures—Of primary importance in checking the computer program is the correlation of computed model sur-

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[3] M. Sibulkin, "Heat Transfer Near the Forward Stagnation Point of a Body of Revolution," *J. Aero. Sci.* **19**, Aug. 1952, 570–571.

[4] E. R. G. Eckert and R. M. Drake, Jr., *Analysis of Heat and Mass Transfer,* McGraw-Hill, New York, 1972.

[5] R. J. Goldstein, G. Shavit, and T. S. Chen, "Film Cooling Effectiveness with Injection through a Porous Section," *J. Heat Transfer* **87**, Aug. 1965, 353–361.

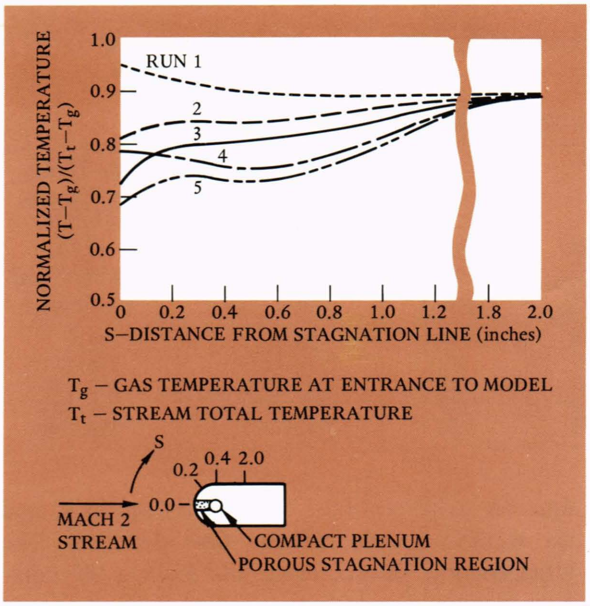

Fig. 8—Summary of computed surface temperatures at the center.

face temperatures with experiment. A summary of computed values for all five runs is presented in Fig. 8. The results show a striking similarity with the plot of experimental values (Fig. 6). The computed results follow the same general contours of the experimental data.

However, the computed values are somewhat lower than measured especially at the stagnation line where the experimental temperatures lie approximately half way between the analytically determined temperatures and the temperatures for zero transpiration cooling.

The relatively large temperature difference at the stagnation line is likely due to the effect of free-stream turbulence in the nozzle. Experimental data previously presented[6] indicate that for a cylinder in subsonic crossflow the stagnation line heat transfer coefficient is nearly doubled at turbulence levels as low as 2.3%. This increase in stagnation line heating could account for the differences in Figs. 6 and 8.

Correlation of Nitrogen Temperature Rise Along Plenum and Correlation of Plenum Static Pressure—Measured and computed steady-state values of nitrogen plenum gas pressure (P_5) and temperature at plenum outlet (T_{18}) are presented in Table 1. The pressures computed from the CTC program were all in general agreement with experimental values, indicating that this portion of the computer program was performing satisfactorily. In contrast to the pressure results, experimental and analytical results for nitrogen gas temperature at the plenum outlet were not in as good agreement. In Runs 2 and 3 (Table 1) measured exit gas temperatures were significantly higher than calculated values, and in Runs 4 and 5 they were lower. It is possible that the combined effect of inlet temperature prediction and thermal conduction of the thermocouple may be responsible for the lack of agreement between measured and computed coolant exit temperature.

Two-Dimensional Crossflow Results—An analysis of the central section of the model was undertaken using the TDTC computer program. The analytical model is presented in Fig. 9 along with the results. In the analysis, temperatures of the solid elements and the total transpirant flow rate were held constant at values previously predetermined in the CTC program. Aerodynamic heating rates at the outer surface were adjusted for local blowing. The steady-state results indicate

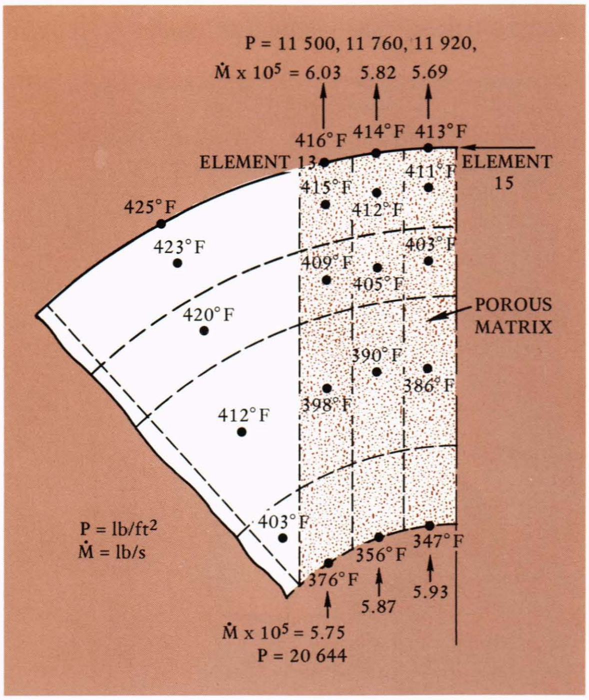

Fig. 9—Temperature and mass flow in porous matrix as computed from two-dimensional transpiration cooling program (TDTC).

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[6] J. Kestin, P. F. Maeder, and H. H. Sogin, "The Influence of Turbulence on the Transfer of Heat to Cylinders Near the Stagnation Point," *Z. Angew. Math. u Phys. (ZAMP)* **12**, 1961, 115–131.

that at the outer surface the transpirant flow rate increases away from the stagnation line and that there is very little temperature gradient at the outer surface of the porous matrix. This indicates that two-dimensional internal crossflow of the coolant had relatively little influence on the measured surface temperature.

Summary

A computer program has been written to predict temperature, pressure, and mass flow in a compact transpiration cooling system. It is a complex program including: conduction, radiation, aerodynamic heating, material properties as functions of temperature, friction losses, conduction to the plenum gas, suction effects, blowing effects, and transpiration cooling.

To verify results obtained from this program, a completely instrumented compact transpiration-cooled leading-edge model was constructed. The data from these tests were compared with analytical values and showed good agreement for absolute pressure in the compact plenum. Measured and computed surface temperatures had the same general trends and were in good agreement every place except in the stagnation region, where it was felt that free-stream turbulence may have caused experimental temperatures to be higher than predicted.

A second computer program has been written to predict three-dimensional temperature, pressure, and mass flow in a porous matrix of general geometry. The program accounts for three-dimensional mass flow of transpirant within a matrix of spatially varying porosity. It is of general form and can be used in other transpiration cooling applications besides the compact plenum application.

Acknowledgment

This work was carried out under sponsorship of the Naval Air Systems Command, specifically, AIR-320B, Lt. Cdr. F. Cundari. Thanks are extended to L. B. Weckesser for his continued guidance throughout this program, and to J. L. Rice for his contribution in carrying out the free-jet tests.

HONORS AND AWARDS

R. E. Gibson, Director Emeritus of the Applied Physics Laboratory and Professor of Biochemical Engineering at The Johns Hopkins University School of Medicine, was awarded the honorary degree of Doctor of Medicine by The Johns Hopkins University on May 26, 1972.

A. Kossiakoff, Director of the Applied Physics Laboratory, has been named a trustee of the Chesapeake Research Consortium. This is an association of academic institutions consisting of The Johns Hopkins University, the University of Maryland, the Virginia Institute of Marine Science, and the Smithsonian Institution. Chartered in January 1972, its mission is "to conduct an integrated and collaborative research program which will contribute to better management of the Chesapeake Bay."

The *APL Technical Digest* won a Certificate of Achievement in the Corporate Research Journal category at the Third International Publications Competition sponsored by the Society for Technical Communications. Accepting the award during the Society's Nineteenth Annual Conference, held May 10–13, 1972, at the Statler Hilton Hotel in Boston, were the *Digest's* Managing Editor P. E. Clark and Staff Artist J. H. Hartle. The winning entry (January–February 1970 issue) was the same one that won the Award of Distinction last year in local competition of the Washington area chapter of the Society.

In a recent contest held by the Washington, D.C. Chapter of the Society for Technical Communications, APL publications won an award in each of the five categories. In addition, a special award was given APL in recognition of its high performance as a multiple winner for two consecutive years. The awards were presented at a dinner on June 23, 1972.

An Award of Excellence was received in the Technical Reports category for *Heat-Engine/Mechanical-Energy-Storage Hybrid Propulsion Systems for Vehicles—Final Report;* editor R. T. Kroll and authors G. L. Dugger, A. Brandt, J. F. George, L. L. Perini, D. W. Rabenhorst, T. R. Small, R. O. Weiss. An Award of Excellence was also received in the House Organ category for the *APL Technical Digest,* Vol. 10, Nos. 4/5; Managing Editor P. E. Clark and Chairman of the Editorial Board S. N. Foner; authors H. B. Riblet, M. R. Peterson, D. L. Zitterkopf, E. J. Hoffman, A. L. Lew, F. F. Mobley, B. E. Tossman, G. H. Fountain.