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Summary

The potential for rocket engine coolant channel flow stratification was computationally investigated. A conjugate, three-dimensional, conduction/advection analysis code (SINDA/FLUINT) was used. Core fluid temperatures were predicted to vary by over 360 deg K (650 deg R) across the coolant channel, at the throat section, indicating that the conventional assumption of a fully mixed fluid may be extremely inaccurate. Because of the thermal stratification of the fluid the walls exposed to the rocket engine exhaust gases will be hotter than an assumption of full mixing would imply. In this analysis, wall temperatures were 160 deg K (280 deg R) hotter in the turbulent-mixing case than in the full-mixing case. Furthermore, the discrepency between the full-mixing and turbulent-mixing analyses increased with increasing heat transfer. Both analysis methods predicted identical channel resistances at the coolant inlet, but in the stratified analysis the thermal resistance increased over 25 percent as the fluid was heated and in the full-mixing analysis the increase in thermal resistance was negligible. The implications of this study are significant. Neglect of thermal stratification could lead to underpredictions in nozzle wall temperatures. Even worse, testing at subscale conditions may be inadequate for modeling conditions that would exist in a full-scale engine. Experimental evidence indicates that the postulate of thermal stratification agrees with rocket coolant channel measurements. More extensive numerical and experimental programs should be undertaken to better define the extent of thermal stratification that occurs in an actual rocket engine.

Introduction

Most liquid propellant rocket engines being designed for future launch or space-based applications employ regenerative thrust chamber cooling, where one of the propellants, usually hydrogen, is used to cool the wall of a rocket nozzle prior to its injection as a propellant. With this system, accurate knowledge of coolant fluid conditions is essential in order to design coolant channels that provide adequate cooling and at the same time minimize coolant pressure drops. Ideally, both axial and peripheral distributions of coolant temperatures and velocities should be known while undertaking the task of coolant channel design. Unfortunately, the nearly limitless possibilities of coolant chamber design are not conducive to the detailed experimental and/or analytical effort that would be highly desirable. Instead, a more simplistic method for determining cooling ability is often employed in design. Heat transfer predictions for regeneratively cooled rocket engines are often performed, with varying degrees of success, by assuming that the coolant behaves like a slug flow. That is, significant thermal variations throughout the core of the fluid are neglected. In this procedure, only axial gradients of fluid temperature are accounted for, with radial and circumferential temperature gradients receiving little attention, being accounted for only in a global correction factor that fits previous experimental results. Unfortunately, such a procedure may be inadequate because the correction factor is a variable of unknown magnitude except for the geometries and boundary conditions that have been tested. In order to improve on current designs and experimental procedures, it is important that the extent of fluid temperature variations in all directions, which are caused by nonuniform fluid heating and asymmetrical geometries, be known. Consequently, the effect of flow stratification on coolant channel design and experimental procedures needs to be evaluated.

The potential for extensive thermal variations in the coolant channels of a regeneratively cooled rocket nozzle is significant. First, heat fluxes will vary considerably around the periphery of a coolant channel, being nearly adiabatic on one side but large on the side closest to the rocket engine exhaust gases. Second, significant temperature gradients perpendicular to the flow direction are known to exist throughout the nozzle liner, even though the liner is usually made of a very high-thermal-conductivity material, such as copper. Consequently, knowing that the copper liner is not isothermal, the full-mixing assumption for the coolant would require that heat transfer be significantly more efficient within the fluid than in copper — a very demanding situation, even with turbulent flow conditions, because the thermal conductivity of copper is about 1500 times greater than the thermal conductivity of liquid hydrogen.[1] The extent and the consequences of incomplete thermal mixing of liquid hydrogen when it is acting as a rocket engine coolant are computationally investigated in this study.

[1] Conditions at 167 K (300 °R) and 8.27 MPa (1200 psia).

Background

Concerns regarding the effect of limited fluid mixing capabilities are not new. In 1963, Reynolds (ref. 1) reported analytical predictions concerning how circumferential distributions of heat flux affect turbulent flow in a tube. This condition is very common and of important concern in the nuclear power industry, where variable heat loads exist around coolant tubes. In fact, consideration of the decreased coolant ability of the fluid due to nonuniform heating is a standard calculation procedure in nuclear power plant designs (ref. 2).

Conversely, the author was unable to find any analytical or experimental studies expressing a similar concern in the design of regeneratively cooled rockets. However, the data seem to indicate that extensive rocket coolant stratification is present. In work reported by Quentmeyer (ref. 3), correlation of measured wall temperatures with analysis required seemingly large peripheral variations (according to a private communication with R. Quentmeyer) in coolant channel boundary conditions. As discussed in a later section, these large variations indicate that limited coolant mixing exists.

Rocket Engine Simulation

Spoolpiece simulation.—In order to assess the potential extent of fluid stratification, a plug-and-spool copper rocket engine configuration (fig. 1) was analyzed. The associated heat flux conditions assumed with the spoolpiece rocket simulation are shown in figure 2, with the heat flux profile being based on those reported by Roncace and Quentmeyer (ref. 4). Simulation was limited to the region from the exhaust gas outlet (coolant inlet) to the rocket throat region. Conditions in the combustion chamber were not considered in this study. The maximum heat flux condition assumed in this simulation was 108 MW/m^2 (66 Btu/in.^{2}-sec). This condition is reflective of current Earth- and space-based rocket engine designs (refs. 5 and 6).

Coolant channel simulation.—The coolant channel geometry simulated in this study is shown in figure 3. It represents a relatively high-aspect-ratio coolant channel for a rocket engine. High-aspect-ratio coolant channels are currently being considered for advanced rocket engines because they offer favorable heat transfer characteristics (ref. 7). A high-aspect-ratio coolant channel geometry was chosen for the following reasons:

(1) The assumptions implied in this study, discussed later, are best suited for a spoolpiece rocket, high-aspect-ratio coolant channel geometry.

(2) Such a geometry represents a rather extreme case in fluid mixing abilities. That is, with smaller channels, the copper ribs would more likely tend toward isothermal conditions, thereby reducing the extent of thermal stratification.

The coolant flow rate, inlet temperature, and properties used in this study are shown in table I. Coolant properties represent conditions at 167 K (300 °R) and 8.27 MPa (1200 psia) (ref. 8). The thermal conductivities for the copper spoolpiece simulation used in this study are included as table II (ref. 9). Arguably, evidence of hydrogen thermal stratification does not hinge on the variability of thermal conductivity. However, the variation was included because the input table already existed and the added computational time was minimal.

Heat Transfer Analysis

Fluid/structural analysis.—A three-dimensional conduction/convection analysis was performed to evaluate the extent of thermal mixing within the coolant channel. Version 2.3A of the SINDA/FLUINT computer code (developed under NASA contract NAS9–17448) was employed, using a discretized structural model as shown in figure 4(a). In addition to the material elements shown in this figure, surface elements on both the chamber wall and the hot side of the coolant channel were employed in order to increase the accuracy of the fluid and liner temperature predictions.

Fluid flow modeling was accomplished by creating "one-way conductors," which allow heat to transfer only in one direction. This is representative of modeling energy transport by bulk fluid transport (i.e., advection). In order to model mixing within the fluid, discretization of the coolant fluid, similar to the discretization of the structural model, was done (fig. 4(b)). The fluid elements were packed nearest the rocket engine exhaust gases to reflect the increased heat transfer that occurs in this region.

The heat transfer from one fluid element to another in the cross-stream direction was modeled as if the fluid element were a solid element. However, instead of a material's thermal conductivity being required to calculate heat transfer resistances, resistances in the fluid model were reflected in the use of a turbulent thermal conductivity k_t. As is evident from the fluid discretization, the emphasis in this study was on examining fluid temperature gradients that may exist in the z direction, with fluid conditions assumed to be relatively well mixed in the y direction. Boundary conditions and dimensional arguments show this to be a valid assumption. Both fluid boundary conditions in the z direction allow heat transfer, whereas the half-channel analysis presumes adiabatic conditions in one of the y-direction boundaries. Furthermore, the physical distance between the channel boundaries is more than an order of magnitude greater in the z direction than in the y direction.

Heat transfer from a solid wall element to a fluid element was modeled by employing the Dittus-Boelter correlation (ref. 10):

$$\mathrm{Nu} = 0.023\ \mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \tag{1}$$

Most rocket engine design procedures use an expression that is similar to equation (1) but further corrected for fluid property variations across the shear layer. They normally employ a ratio of wall to bulkhead temperature T_w/T_b raised to some power n as suggested by Hendricks ($n = -1/2$, ref. 11). However, in this study no correction was made in order to isolate the qualitative phenomenon of fluid stratification and avoid extraneous complications.

Fluid mixing model.—In order to assess the magnitude of coolant thermal stratification that may exist in a rocket engine coolant channel, several simplifying conditions were assumed in this study. It was assumed that the turbulent heat transfer characteristics in the "core" of the hydrogen coolant channel could be characterized by using turbulent data from pipe flow. This is in line with the application of a "hydraulic diameter" concept (ref. 12) for estimating surface heat transfer characteristics in a noncircular duct by using pipe flow data. However, in this analysis, where the internal fluid temperature distributions are of concern, the pipe flow assumption also allowed an additional simplification in that it removed consideration of the internal heat transfer effects of secondary flow. Because a spoolpiece rocket engine does not have the curvature of a conventional converging-diverging rocket engine, and because high-aspect-ratio coolant channels approach an infinite channel condition, neglecting secondary flow (i.e., assuming that the coolant velocity has no nonaxial mean velocity component) is a good assumption when analyzing the type of coolant channel configuration described herein.

By using the turbulent-pipe-flow similarity assumption, the following expression for the ratio of the average turbulent conductivity in the nonshear direction $(k_t)_z$ to the fluid thermal conductivity can be obtained as a function of the Reynolds number Re_{D_H}.

$$\frac{(k_t)_z}{k} = 0.008\ \mathrm{Re}_{D_H}^{0.9} \tag{2}$$

This relation is derived in the appendix. It is worth noting that this expression, when used at the fluid properties of interest listed in table I, yields $(k_t)_z$ = 89.7 W/m-K (0.0012 Btu/in.-sec-°R). This is approximately 20 percent of the thermal conductivity of copper (table II), thus providing an initial indication that significant fluid thermal gradients will exist.

Results and Discussion

There were three primary concerns in the thermal stratification study: the effect of thermal stratification on wall temperatures, scaling concerns, and experimental concerns. Differences in predicted material wall temperatures between the turbulent-mixing analysis, which assumes that the transfer of heat in the nonflow direction is governed by the turbulent conductivity expression of equation (2), and a full-mixing analysis, which assumes that there are no fluid temperature gradients in the nonflow direction, an assumption obtainable by setting the turbulent thermal conductivity $(k_t)_z$ to infinity, were of primary concern as the purpose of coolant channels is to maintain material temperatures at a safe operating condition. Another concern with the study was the effect of scaling. Because rocket engines would never be constructed and used based solely on analytical predictions, and would most likely be tested and screened in a subscale environment, differences between subscale and full-scale results would be an important contribution. Finally, the effect of thermal stratification on experimental research programs is important because future rocket engines will require the interaction of experiment and analysis if high-performance coolant channels are desired. The three concerns of this study are outlined in the following sections, where the throat region and the hot-gas-side metal temperatures are examined.

Effect on wall temperatures.—The fluid and wall temperatures at the throat are shown in figure 5 for both the full-mixing and turbulent-mixing cases. The two analysis methodologies predict substantially different temperatures in the fluid and the wall. The turbulent-mixing condition predicts fluid temperature variations of more than 360 deg K (650 deg R). This is a tremendous variation and reflects stratified flow rather than fully mixed flow.

The limited extent of fluid mixing results in greater variations in wall temperature as well. On the hot-gas-side, wall temperatures predicted by using the turbulent-mixing assumption are 160 deg K (280 deg R) higher than temperatures predicted by using a full-mixing assumption. On the cold side wall temperatures are 50 deg K (90 deg R) lower with the turbulent-mixing assumption.

Scaling concerns.—The deviation in predicted hot-side wall temperatures between the two fluid models is shown in figure 6. In an idealized case the overall thermal resistance, which is the ratio of the difference between the maximum metal temperature and the average fluid temperature, to the surface heat flux, $(T_H - T_c)/q''$, is constant. The full-mixing analysis approaches this condition, with only slight deviation because the analysis of the copper liner considered both axial conduction and temperature-dependent properties. Conversely, the overall thermal resistance in the turbulent-mixing case increases monotonically as the fluid is heated, with effective resistances at the throat being 25 percent higher than predicted for the full-mixing case. This reflects the deleterious effect of coolant thermal stratification on rocket cooling. Initially, as the fluid enters at a uniform temperature, stratification is not present. However, as the coolant becomes increasingly heated, the fluid closest to the rocket engine exhaust gases receives a disproportionate amount of heat. Hence, thermal gradients begin to rise within the core of the coolant because the coolant is unable to adequately distribute (by turbulent mixing) the nonuniform heating that occurs around the periphery of the channel. As a result, the extent of flow stratification becomes increasingly significant as the extent of heating increases. The overall thermal resistance of the coolant channel configuration in the turbulent-mixing case is 25 percent higher at the throat than at the inlet. This is a tremendous increase in overall resistance and completely overshadows traditional concerns of rocket engine thermal design, such as the optimal selection of a copper alloy.

Besides the magnitude of the effective fluid resistance borne out in figure 6, the monotonically increasing nature of this effective resistance is also cause for concern. Many rocket engine subscale tests attempt to match throat heat flux conditions rather than the heat flux profile. The results of this study indicate that the extent of fluid heating is also very important. In general, most subscale tests also correspond to subscale heating rates, and results obtained at these conditions may substantially underestimate wall temperatures that will exist in an actual rocket engine.

Experimental concerns. – As described previously, cold-side wall temperatures at the throat are predicted to be signficiantly lower in the turbulent-mixing case. In fact, cold-side wall temperatures in the turbulent-mixing case are 30 deg K (50 deg R) lower than the average fluid temperature, as can be seen by comparing the metal temperatures in figure 5(b) with the fluid temperatures in figure 5(a). The prediction of wall temperatures lower than the average fluid temperature has significant experimental and design implications. In performing heat transfer measurements in a rocket engine it is a common practice to measure wall temperatures in the copper liner. After measuring wall temperatures and using previously obtained surface heat flux data, coolant heat transfer coefficients are varied around the perimeter of the channel until agreement with experimentally measured temperatures is obtained. Consider now the wall temperature distribution predicted with the turbulent-mixing analysis, and assume that this temperature distribution was supported by experimental measurement. Any analytical attempts to match this temperature distribution by assuming a fully mixed fluid would require a negative heat transfer coefficient – a violation of the second law of thermodynamics.

Concluding Remarks

The results of this coolant channel study indicate that incomplete fluid mixing is a distinct possibility in rocket engines. A turbulent-mixing analysis predicts temperature variations in the core of the fluid greater than 360 deg K (650 deg R). The consequences of incomplete fluid mixing are significant. First, much more serious attention must be paid to fluid mixing in the testing and design of rocket engines. Point tests, such as matching heat fluxes and coolant channel geometry only at the throat, are inadequate. Greater consideration of a complete engine heat transfer simulation is essential. Also, the consideration of stratified coolant flow may significantly alter coolant channel designs because the effective resistance to heat transfer may be substantially higher than would exist with a fully mixed case. Consequently, coolant channels should be designed to maximize fluid mixing.

Experimental verification of this study is necessary. From this study one can only conclude that thermal mixing could be a major concern in regeneratively cooled rockets engines. Because significant assumptions concerning the fluid flow have been employed, a more detailed numerical analysis, which would employ advanced fluid modeling techniques, should also be pursued. However, considering the extensive amount of thermal stratification predicted in this analysis, it is unlikely that a more advanced analysis would indicate that thermal stratification is of negligible concern.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 22, 1992

Appendix – Derivation of Turbulent Thermal Conductivity

In the estimation of turbulence transport properties in a high-aspect-ratio coolant channel the desired relation for the turbulent thermal conductivity in the nonshear direction $(k_t)_z$, which is necessary to model interfluid heat transfer, will be established by using relations and measurements developed for estimating the nonshear direction in a pipe, the θ direction.

The ratio of circumferential turbulent to fluid thermal conductivity $(k_t)_\theta / k$ can be expanded and written in the form of the following nondimensional variables:

$$\frac{(k_t)_\theta}{k} = \frac{(\varepsilon_t)_r}{\nu} \frac{\Pr}{(\Pr_t)_r} \frac{(k_t)_\theta}{(k_t)_r} \tag{A1}$$

A relationship for the ratio of radial turbulent to fluid kinematic viscosity in the core of a pipe $(\varepsilon_t)_r / \nu$ is developed by Hinze (ref. 13, p. 730) and is of the form

$$\frac{(\varepsilon_t)_r}{\nu} = \frac{C}{2} \mathrm{Re}_D \sqrt{\frac{f}{8}}, \quad C \simeq 0.07 \tag{A2}$$

A correlation relating the friction factor f to the Reynolds number (ref. 12, p. 382) is

$$f = 0.184\ \mathrm{Re}_D^{0.2} \tag{A3}$$

Substitution and simplification yield

$$\frac{(\varepsilon_t)_r}{\nu} = 0.0053\ \mathrm{Re}_D^{0.9} \tag{A4}$$

Turbulent Prandtl number $\Pr_t$ values of about 0.7 have been reported near the center of a duct (ref. 14, p. 431). This is close to the fluid Prandtl number of hydrogen (0.728 at 167 K (300 °R) and 8.27 MPa (1200 psia)), thus justifying the following relation:

$$\frac{\Pr_t}{\Pr} = 1 \tag{A5}$$

The ratio of circumferential to radial thermal conductivity $(k_t)_\theta / (k_t)_r$ has been measured by A. Quarmby and R. Quirk (ref. 15) and the relation

$$\frac{(k_t)_\theta}{(k_t)_r} = 1 + \frac{0.2}{1.02 - 2r/D} \tag{A6}$$

has been suggested as an approximate fit to the data (ref. 16). In the fully turbulent core, $0 < 2r/D < 0.8$, the experimental data and the correlation of equation (A6) suggest that the ratio of circumferential to radial turbulent conductivity is reasonably constant and has a value of 1.5. Thus, using the relation

$$\frac{(k_t)_\theta}{(k_t)_r} = 1.5 \tag{A7}$$

and combining relations developed in equations (A5) and (A4) into equation (A1) yield

$$\frac{(k_t)_\theta}{k} = 0.008\ \mathrm{Re}_D^{0.9}$$

The following relation is extended to high-aspect-ratio channels by use of a hydraulic diameter ($D_H = 4A/P$) in the calculation of Reynolds number:

$$\frac{(k_t)_z}{k} \simeq \frac{(k_t)_\theta}{k} = 0.008\ \mathrm{Re}_{D_H}^{0.9} \tag{A8}$$

References

1. Reynolds, W.C.: Turbulent Heat Transfer in a Circular Tube With Variable Circumferential Heat Flux. Int. J. Heat Mass Transfer, vol. 6, 1963, pp. 445–454.
2. Hoffman, M.A., et al.: Fusion Reactor First-Wall Cooling for Very High Energy Fluxes. Nuc. Eng. Des., vol. 36, 1976, pp. 37–46.
3. Quentmeyer, R.J.: Experimental Fatigue Life Investigation of Cylindrical Thrust Chambers. NASA TM X-73665, 1977.
4. Roncace, E.S.; and Quentmeyer, R.J.: Hot-Gas-Side Heat Transfer Characteristics of a Subscale Plug-Nozzle Rocket Chamber. NASA Technical Memorandum to be published in 1992.
5. Advanced Expander Test Bed Engine—Preliminary Design. United Technologies, NASA CR-187081, 1991.
6. The Space Transportation Booster Engine Phase A Study, Vol. II—Final Report. (RI/RD88-230-2-VOL-2, Rockwell International/ Rocketdyne Division; NASA Contract NAS8-36856), NASA CR-179406, 1987.
7. Quentmeyer, R.J.: Rocket Combustion Chamber Life Enhancing Design Concepts. AIAA Paper 90-2116, July 1990. (Also, NASA CR-185257.)
8. McCarty, R.D.: Hydrogen Technological Survey—Thermophysical Properties. NASA SP-3089, 1975.
9. Touloukin, Y.S.; and Ho, C.Y., eds.: Thermophysical Properties of Matter. Plenum Press, New York, Vol. 1, Thermal Conductivity of Metallic Solids, 1972.
10. Dittus, F.W.; and Boelter, L.M.K: Heat Transfer in Automobile Radiators of the Tubular Type. University of California, Publications in Engineering, vol. 2, no. 13, 1930, p. 443–461.
11. Hendricks, R.C., et al.: Bulk Expansion Factors and Density Fluctuations in Heat and Mass Transfer. XVth International Conference of Refrigeration—Proceedings, Vol. II, pp. 45–53, 1979.
12. Incropera, F.P.; and Dewitt, D.P.: Fundamentals of Heat Transfer. John Wiley & Sons, 1981.
13. Hinze, J.: Turbulence, 2nd ed., McGraw-Hill, 1975.
14. Burmeister, L.C.: Convective Heat Transfer. John Wiley & Sons, 1983.
15. Quarmby, A.; and Quirk, R.: Measurements of the Radial and Tangential Eddy Diffusivities of Heat and Mass in Turbulent Flow in a Plain Tube. Int. J. Heat Mass Trans., vol. 15, 1972, pp. 2309–2327.
16. Gartner, D.; Johannsen, K.; and Ramm, H.: Turbulent Heat Transfer in a Circular Tube With Circumferentially Varying Thermal Boundary Conditions. Int. J. Heat Mass Trans., vol. 17, 1974, pp. 1003–1018.

TABLE I. – HYDROGEN COOLANT FLOW RATE AND PROPERTIES USED IN THERMAL STRATIFICATION ANALYSIS

[Properties evaluated at 167 K (300 °R) and 8.27 MPa (1200 psia).]

Coolant flow rate per channel, kg/sec (lbm/sec)	3.789×10^{-3} (8.353×10^{-3})
Coolant inlet temperature, K (°R)	33.3 (60.0)
Specific heat, kJ/kg-K (Btu/lbm-°F)	17.06 (4.076)
Thermal conductivity, W/m-K (Btu/in.-sec-°R)	0.1543 (2.064×10^{-6})
Dynamic viscosity, N-s/m^2 (lbm/ft-sec)	6.58×10^{-6} (0.442×10^{-5})

TABLE II. – PROPERTIES OF PURE COPPER

Temperature		Thermal conductivity, k	
K	°R	W/m-K	Btu/in.-sec-°R
30.0	54.0	4300	5740×10^{-5}
35.0	63.0	2900	3880
40.0	72.0	2050	2740
45.0	81.0	1530	2050
50.0	90.0	1220	1632
60.0	108.0	850	1140
70.0	126.0	670	896
80.0	144.0	570	762
90.0	162.0	514	687
100.0	180.0	483	646
150.0	270.0	428	572
200.0	360.0	413	552
250.0	450.0	404	540
273.2	491.8	401	536
300.0	540.0	398	532
350.0	630.0	394	527
400.0	720.0	392	524
500.0	900.0	388	519
600.0	1080.0	383	512
700.0	1260.0	377	504
800.0	1440.0	371	496
900.0	1620.0	364	487
1000.0	1800.0	357	478
1100.0	1980.0	350	468
1200.0	2160.0	342	457
1300.0	2340.0	334	447
1356.0	2440.8	330	441

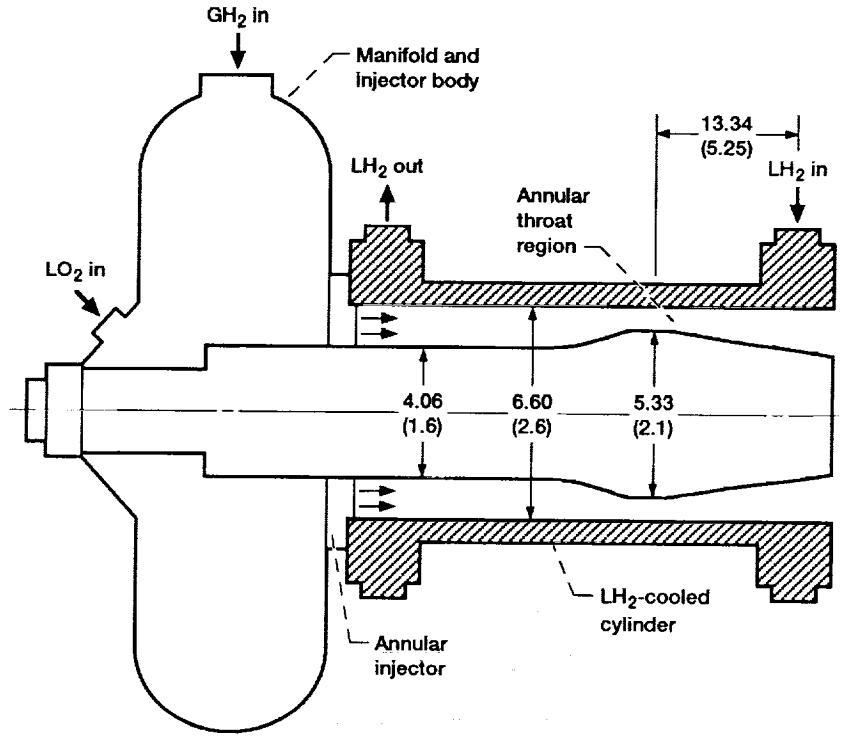


Figure 1.—Schematic of cylindrical thrust chamber assembly. (Dimensions are in centimeters (inches).)

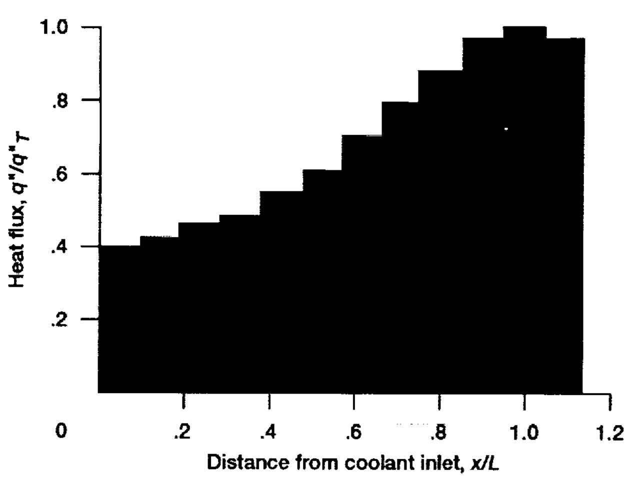


Figure 2.—Heat flux profile applied to coolant stratification study. Coolant-inlet-to-throat distance, L, 13.34 cm (5.25 in.); heat flux at throat, q''_T, 108 MW/m^2 (66 Btu/in.^{2}-sec).

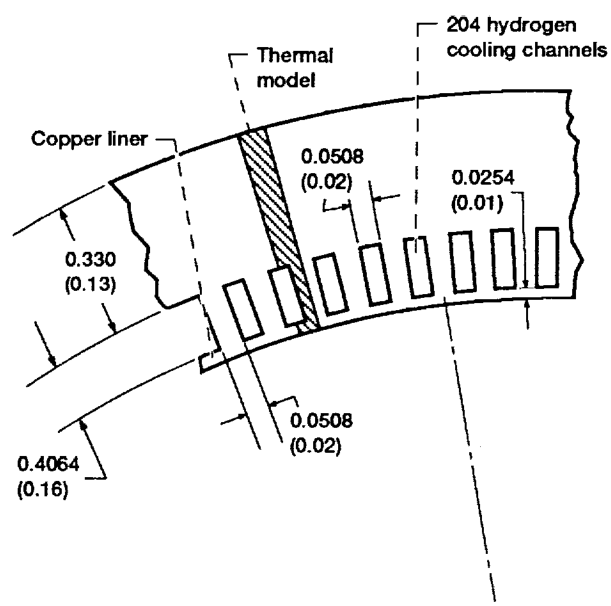
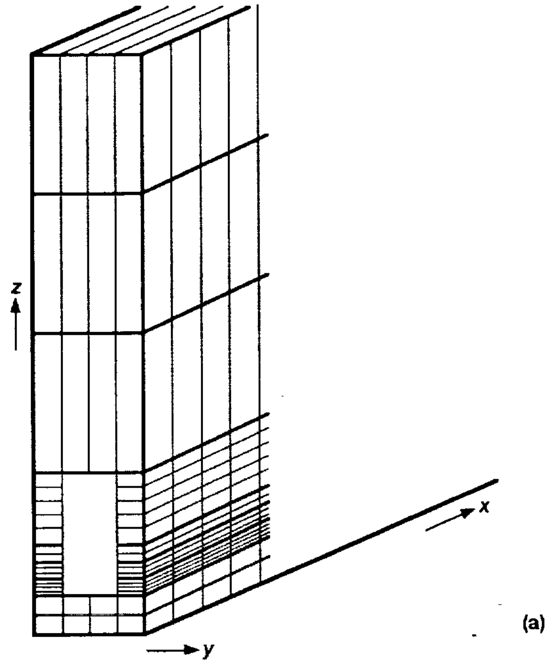
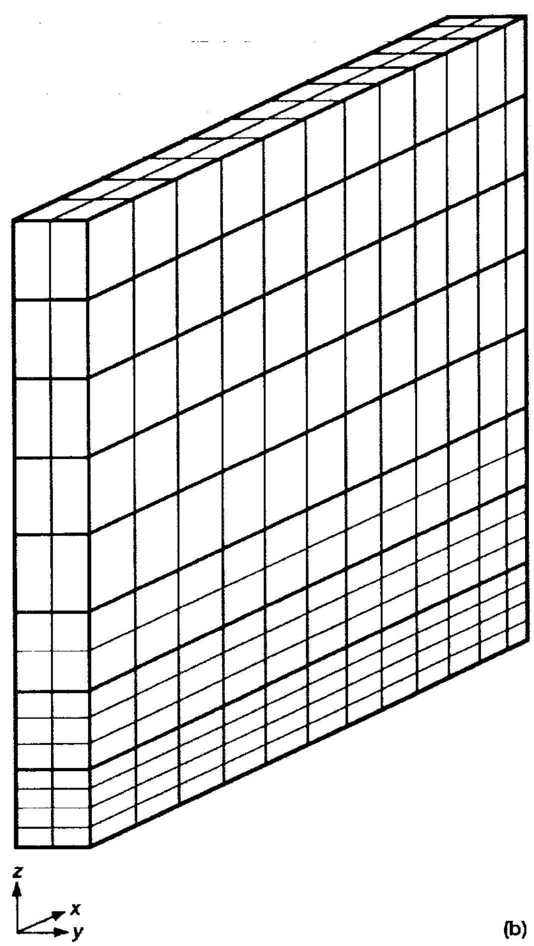


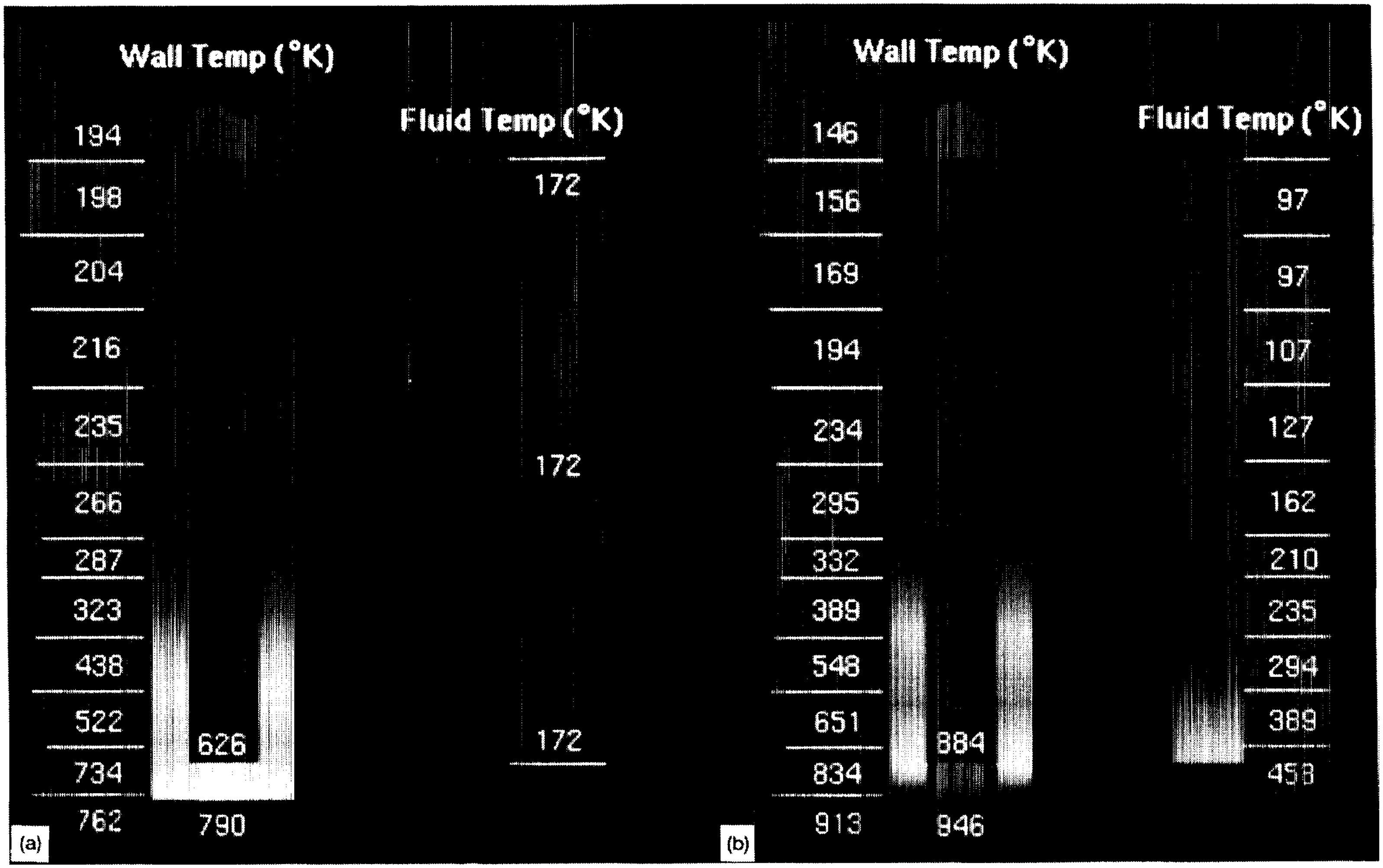
Figure 3.—Geometry of spoolpiece cross section.





(a) Spoolpiece liner.
(b) Coolant.

Figure 4.—Discretized structural model.



(a) Conventional analysis (full-mixing assumption).
(b) Advanced heat transfer analysis (turbulent-mixing assumption).

Figure 5.—Predicted temperature distribution at spool throat section of plug-and-spool rocket engine.

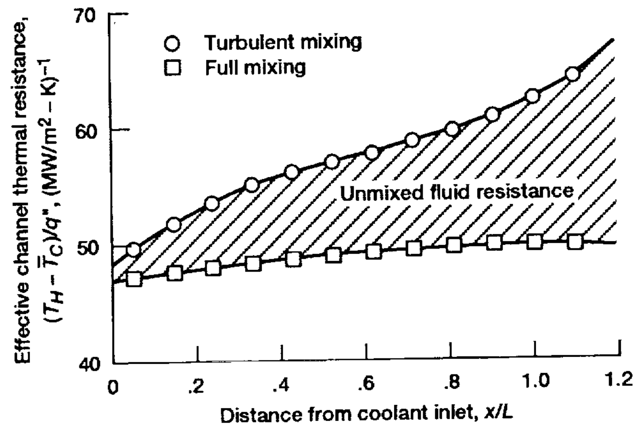


Figure 6.—Increase in effective coolant channel thermal resistance due to stratified thermal coolant flow. Coolant-inlet-to-throat distance, L, 13.34 cm (5.25 in.).

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