JUL 29 1965

LA-AC-7224

MASTER

CONF-650611-2

84796

HEAT TRANSFER IN MISSILES AND SPACE OPERATIONS*

by

Keith Boyer

University of California, Los Alamos Scientific Laboratory

Los Alamos, New Mexico

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HEAT TRANSFER IN MISSILES AND SPACE OPERATIONS

Introduction

The great adventure of manned exploration of space is underway, but road maps and time tables have not been printed beyond the first way station at the moon. Although the United States' manned space program has not been defined beyond Apollo, the moon landing program, a large effort is under way to solve some of the problems of manned interplanetary exploration. The mission which has been studied in the greatest detail is the manned Mars landing.

The Apollo mission is scheduled to use liquid-hydrogen liquid-oxygen chemical propulsion systems for all stages above the first, with a single launch. The manned Mars mission studies start with a million-or-more-kilogram, multistage, nuclear-powered vehicle assembled in a low earth orbit. Under the most favorable circumstances, the trip will take 400 to 500 days and may involve a swing by Venus enroute.

The hydrogen-oxygen engine introduced many new problems in heat transfer processes at cryogenic temperatures. Many have been sharply defined and at least partially solved. However, the nuclear propulsion system development, together with constraints imposed by the missions in which it is to be employed, has extended the number and scope of these problems many-fold. While some have been solved, many cannot even be clearly defined. Even the experimental tools and techniques necessary to investigate them have either not been developed or are just becoming available. These problems include the storage of hydrogen in space for periods up to a year or more with the accompanying problems of insulation, pressurization, venting or re-liquifaction, and

configuration control, and the problem of nuclear radiation heating of liquid hydrogen and the resulting flow behavior.

This paper will review a number of areas of interest in heat transfer studies at cryogenic temperatures which apply principally to propulsion system problems and will point out problems which need further investigation. Particular aspects of some of the problems mentioned here are discussed in much greater detail in papers presented by others at this meeting.

Storage of Liquid Hydrogen

Long-term storage of cryogenic hydrogen in a stage tank in space presents many problems. The use of super-insulation reduces the heat flux sufficiently to make long-term storage feasible, but a number of practical problems remain.

The management of the vapor and liquid configurations is of great importance in the storage vessel, as separation of vapor and liquid and proper placement of each in the container is essential to permit venting of the vapor during storage and the expulsion of the liquid during startup and operation of the propulsion system. In zero-g situations, the behavior of the interface between liquid and vapor is dominated by the surface tension forces. The contact angle between the vapor-liquid interface and the containing walls, whose cosine is given by the ratio of the difference in surface energies of the vapor and liquid phases with respect to the walls over the vapor-liquid interface surface energy, is largely instrumental in determining the equilibrium configuration. If the contact angle is less than 90° , the liquid will wet, and if it is greater than 90° the liquid will not wet, the walls. The use of a minimum surface energy principle permits the design of capillary baffles and screens to control the liquid position.

To determine the zero-g behavior experimentally, drop tower tests, airplane flights along ballistic trajectories, and ballistic rocket flights¹ have been used. A test of the validity of these experiments is necessary because of the limited time in which to establish equilibrium and the sensitivity to small departures from zero gravity. A comparison of the Bond number, the ratio of gravity forces to surface tension forces, and the Weber number, the ratio of hydrodynamic forces to surface tension forces, can be used to evaluate the time interval required for equilibrium and the sensitivity to low-gravity forces.

A review of both experiments and calculations of zero-gravity effects was made by Otto,² of the Lewis Research Center. Heat transfer to the fluid in well-insulated tanks is due to nucleate boiling which is little affected by gravity forces. The lack of convection at zero g results in a slow migration of bubbles through the liquid, producing good heat transfer to the liquid and a homogeneous situation. However, the heat flux can be sufficient to cause pinching off of the wetted surface and development of a dry spot which eventually leads to the separation of gas and liquid in the container. This causes nonequilibrium, with a higher temperature gas and increased venting.

Acceleration perturbations such as attitude control, docking operations, and fluid outflow all affect, and are influenced by, the dynamics of the liquid-vapor interface, which in turn is interrelated with the heat transfer properties. The use of orbiting vehicles to resolve some of the uncertainties and to check scaling laws is planned.

The behavior of ground storage in large dewars is quite different from storage in space owing to the buoyancy forces which result in a very non-homogeneous temperature distribution. An interesting study on self-pressurization of a large storage dewar was made by Liebenberg and Edeskuty³ as shown in Figure 1. The dewars were approximately 200,000 liters each with a boil-off

DEWAR PRESSURIZATION

Figure 1.

rate of 0.18% per day. Since the dewars are in a one-g field, the pressure rise is much greater than in the uniform temperature case, because of non-equilibrium heating. The lower rate for dewar B was due to a helium gas purge leak into the dewar producing convection and moving the hydrogen towards equilibrium.

The amount of pressurization gas needed to expel the liquid is also important. Dewar studies quoted above have shown that for representative flow rates the pressurization gas does not equilibrate with the liquid but acts like a piston in displacing the liquid.

Another problem presenting considerable experimental difficulty is the heating of the hydrogen propellant in the tankage of a nuclear stage by neutron and gamma ray absorption. The energy deposition is readily calculable and is given in Figure 2 for a nonshielded 1000-MW reactor.⁴ However, there are questions about the amount of energy that is stored in chemical bonds, thus reducing the effective heating rates, for times greater than the period of interest. Since 5000-MW reactors are planned for space missions, the inclusion of a shadow shield is necessary because the heating rates would be unacceptable. The behavior of the flow due to this heating is very difficult to calculate or to measure experimentally. The large ratio of buoyancy to viscous and inertial forces in liquid hydrogen should cause convective mixing. This flow pattern is also modified by the propellant flow to the engine. Stage testing may be required to determine this behavior. Fortunately, the stage acceleration is kept above 0.25 g when the engine is operating and the nuclear radiation fluxes are high, so this problem is not complicated by zero-g effects.

Experiments reported by Duke⁵ have been performed on scale-model tanks exposed to flux from a nuclear reactor. An inversion point is predicted near the wall where the downward flow, due to propellant usage, is reversed by

Figure 2.

buoyant forces due to radiation heating. This gives rise to a stratified layer of warm fluid in the vicinity of the vapor-liquid interface. However, the experimental data have not yet been compared with predictions.

Heat Transfer for Forced Convection

Forced convection heat transfer to liquid hydrogen at supercritical pressures has been investigated rather exhaustively from 20 to 165 atmospheres by many experimentors. Most of these measurements were made with straight, electrically heated tubes to establish correlations for nozzle design. In many cases this work was extended to subcritical pressures in the two-phase region.

In the supercritical region the Hess-Kuntz correlation which incorporates a kinematical viscosity parameter (ν_w/ν_B) to modify the Dittus-Boelter equation gives the best fit for experimental data.

$$Nu_t = 0.0208 (Re)^{0.8} (Pr)^{0.4} (1 + 0.014 \nu_w/\nu_B)$$

(where the properties are evaluated at film temperature assumed to be the average of the wall and the bulk temperature)

It is the favored correlation for nozzle design with minor variations in the coefficients and averaging method for the reference temperature. A number of other modifications⁶ using the ratio of specific heats and the ratio of densities, as well as changes in the type of correlation^{7, 8} have been used with almost as good a fit to the data.

However, there are two departures real nozzles make from the idealized experiments. The heat is introduced on one side of the tube only in a real nozzle, and the tubes have a varying curvature due to the nozzle contour. Experiments are now in the planning stage to determine the effects of asymmetrical heating. Some data exist on effect of tube curvature which are

confirmed in nozzle performance. Hendricks and Simon⁹ reported a heat transfer increase of up to a factor of three between the concave and the convex tube wall, with the straight tube corresponding to the convex wall. They found the magnitude of the effect sensitive to the radius of curvature and the proximity of the temperature to the transposed critical line. A factor of three was observed near the transposed critical for hydrogen and a factor of two for gaseous hydrogen. In general, a factor of two improvement in heat transfer over the straight tube values could be expected at the nozzle throat. Hendricks et al. concluded that centrifuging effects were responsible for the increase.

Experiments have been performed by Williamson and Bartlit¹⁰ on a scale model of a hot-water to liquid-hydrogen heat exchanger for use in the nuclear propulsion reactor test facility at the Nuclear Rocket Development Station (NRDS) in Nevada. Liquid hydrogen near the critical pressure was introduced into a 3/4-inch-internal diameter tube 40 feet long with a counter flow of hot water outside the tube. Temperature measurements were made across the tube diameter near the inlet and at a series of stations along the tube. Heat transfer rates were low, with considerable scatter below and near the initial temperature as shown in Figure 3. Transverse temperature distributions indicated a core flow with a more-or-less linear temperature drop from the wall to the tube axis. Liquid nitrogen tests gave heat transfer poorer than that predicted by as much as a factor of twenty five.

A turbulator strip, or swirl inducer, was placed along the tube diameter with one turn every six tube diameters to break up the core flow. The heat transfer was now twice that predicted by the Dittus-Boelter correlation, adjusted to agree with experimental data using bulk properties, but otherwise fitted the correlation over the entire temperature range investigated

Figure 3

RATIO OF THEORETICAL TO EXPERIMENTAL HYDROGEN
HEAT TRANSFER COEFFICIENT VS THE BULK HYDROGEN TEMPERATURE.

DATA BY K.D. WILLIAMSON, CMF-9
J.R. BARTLIT, CMF-9

(40°R to 500°R). A second experiment was conducted on a 4-inch-internal diameter tube 160 feet long, shown in Figure 4. It was tested over a range of pressures up to 70 atmospheres. The heat transfer was in good agreement with the small tube results, and will be reported later this year by Williamson and Bartlit.

The similarity of the swirl generator behavior to the tube curvature data is striking and indicates that, except very close to the transposed critical line, which was not determined in the heat exchanger experiment, the mechanism for enhancement of heat transfer is identical for both situations.

The considerable effort expended on correlating data on heat transfer in straight tubes has produced good predictive techniques except near the critical point. Since such large effects are obtained due to curvature, it is imperative to extend the experimental data and predictive techniques to include curvature, assymetric heating, and critical temperature phenomena to establish a precise basis for design of real configurations such as propellant-cooled nozzle walls. Some effort in this area is now under way.

All of the correlations are questionable near the critical point-- a region of considerable interest in practical heat transfer problems. Investigation of anomalous heat transfer rates in the high pressure region by Hendricks¹¹ revealed the existance of quasi-stable transverse oscillations several kilocycles in frequency, apparently a gas dynamic phenomena associated with flow in pipes. Heat transfer rates as high as five to seven times the minimum values were found. A paper including these measurements is in preparation.

HEAT EXCHANGER EXPERIMENT, NRDS

Figure 4.

Transient Heat Flow

Transient heat flow calculations are important in predicting cryogenic system behavior during chilldown or in reaching some operating condition of interest. A case in point is the determination of the temperature vs time histories along various flow profiles through a nuclear propulsion reactor during startup, in order to choose an optimum route. It is also of interest to predict the transient behavior of the various temperature and pressure profiles during a shift in the operating point or for after-heat removal. A particular concern about the transient behavior in the two-phase flow region arose from the observation that a pound of cold hydrogen in the reactor core produced somewhat more positive reactivity contribution than the control drums could subtract. It was postulated that an error in flow behavior or programming while the core was cold might lead to a destructive power excursion.

A code for digital computation was devised by Thurston and Pollock¹² to calculate the wall temperatures and hydrogen state throughout the reactor as a function of time. A quasi steady-state assumption was introduced by assuming mass flow rate to be constant along the single flow passage which represented each different section of the reactor with all sections joined in series. Energy is introduced into the channel walls at a preprogrammed rate with an arbitrary spacial distribution. Axial heat conduction was neglected to make the calculation one-dimensional. A time dependant diffusion calculation with convective boundary conditions at the flow passage wall and appropriate outer boundary conditions was made to obtain wall temperatures. The heat transfer and pressure loss correlations are given in Figure 5.

The computer code employs finite difference methods to solve the differential equations representing the energy and momentum conservation and equation of continuity. Euler's method applied to a mesh of cells along the channel axis is used to integrate the equations for steady compressible flow.

HEAT TRANSFER
TWO PHASE

$$\left(\frac{hD}{k}\right) = (.000709)(Re_f)^{.656} (Pr_f)^{-13} \left(\frac{\rho_f}{\rho}\right)^{.223} \left(\frac{T_w}{T}\right)^{.212} \text{---(1)}$$

$$\text{where } Re_f = \frac{4\dot{w}}{\pi D \mu_f}$$

GAS

$$\left(\frac{hD}{k}\right) = (.0217)(Re)^8 (Pr)^4 \left(\frac{T_w}{T}\right)^{-.34} \text{---(2)}$$

PRESSURE DROP
TWO PHASE

$$\left(\frac{dP}{dX}\right) = \phi^2 \left(\frac{dP}{dX}\right)_L \text{---(3)}$$

$$\left(\frac{dP}{dX}\right)_L = \frac{f_L V_L^2 \rho_L}{gD} \text{---(4)}$$

$$X^{-1} = \left(\frac{1-Z}{Z}\right)^9 \left(\frac{\rho_g}{\rho_L}\right)^5 \left(\frac{\mu_L}{\mu_g}\right)^{.1} \text{---(5)}$$

$$\left. \begin{aligned} \phi^2 &= 13.05(X)^{1.36} + 2.517, & X \geq 1.11 \\ \phi^2 &= 15.84(X)^{.659}, & X < 1.11 \end{aligned} \right\} \text{---(6)}$$

GAS

$$f = \frac{2h(Pr)^{2/3}}{\rho V C_p} \text{---(7)}$$

FIGURE 5
HEAT TRANSFER AND PRESSURE LOSS CORRELATIONS

The wall temperatures are computed for a number of radial cells associated with each axial cell. An iterative coupling is employed between the wall temperatures and flow equations by using the heat flux from the previous iteration to integrate the flow equations, and the hydrogen temperature resulting is used to correct the wall temperature.

A flow experiment, Figure 6, was made by Watts, Lyle and Balcomb¹³ to check the predictions on a single-tube model of the reflector. Good agreement for the end points and for tube exit conditions was obtained, as seen in Figure 7, but inlet and intermediate wall temperatures were in poor agreement. A cold-flow test on a reactor assembly, complete except for uranium loading, conducted at NRDS, showed good agreement with predictions. A reactor system calculation includes as input data hydrogen reactivity, fission power distribution, neutron and gamma heating of the reflector, and the nozzle-exhaust to coolant-passage heat transfer, and predicts a complete temperature profile.

The results of these calculations and experimental verifications indicated that no disastrous reactivity problems due to liquid hydrogen reactivity would occur, and subsequent reactor tests proved this to be true.

The experiments made on the heat exchanger as described earlier would indicate that the failure of the code to predict wall temperatures near the inlet lies in the assumption of a homogeneous flow with a convective film boundary layer while the real situation is indicated to be a nonhomogeneous flow in the two-phase region. An attempt to improve this calculation was made by Pierce,¹⁴ of Westinghouse Astronuclear Laboratory. This code, referred to as TONE, used a slug-flow model based on experimental observations of temperature fluctuations in heated tubes. Fluid slugs with boiling-heat transfer characteristics are assumed to flow intermittently past a given point thereby

LASL-AEC-OFFICIAL

Figure 6.

LASL-AEC-OFFICIAL

LASL-AEC-OFFICIAL

COMPARISON OF MEASURED WALL TEMPERATURE WITH HEX RESULTS

Figure 7.

LASL-AEC-OFFICIAL

producing a boiling heat transfer region separated by the vapor phase with forced convective heat transfer. The heat transfer is adjusted to experimental data by altering the fraction of time during which the slugs appear.

Figure 8 gives the comparison of the wall temperature history at the inlet of a small tube as calculated experimentally, by TONE, and by using the homogeneous model. The tube outlet wall temperatures were also in good agreement with experiments as were the homogeneous calculations.

In summary, transient heat flux can be calculated for both equilibrium and two-phase nonequilibrium conditions and gives good agreement with experiments. The exact type of flow may vary with inlet conditions and Reynold's number in the two-phase region, and is doubtless more complex than the model assumed for calculation. A homogeneous situation could probably be forced by use of a swirl inducer.

System Dynamics

When liquid hydrogen is permitted to flow from a cold supply system to a warm flow system, a complex spectrum of flow oscillations may result. If the warm system has a heat source, it is possible to excite characteristic frequencies. A number of cases related to heat transfer phenomena are discussed in the paper given by Thurston at this meeting. A quasi-stable, high-frequency mode with greatly enhanced heat transfer rates may exist for high pressure systems due to acoustic modes as discussed earlier. However, experience with massive flow systems used in connection with nuclear propulsion reactions has shown that fairly predictable and easily controlled behavior can be obtained if appropriate conditions are fulfilled.

If the cold system is connected suddenly to a warm system with a high impedance for the resulting gas flow rate, inlet pressure oscillations

INLET WALL TEMPERATURE COMPARISONS Figure 8.

with flow reversal occur. Decreasing the downstream impedance or reducing the rate of flow increase by controlling an impedance between the cold and warm sections reduces and finally eliminates these disturbances. If a steady heat source, such as a heat exchanger, is placed in the warm section, a change in the heat flux or flow rate will cause a damped oscillation. The damping factor is proportional to the ratio of the damping impedance to the cold system flow impedance and is critically damped when the ratio is one or greater. Fortunately, the propulsion reactor has a sufficient damping impedance in the nozzle cooling tubes to permit satisfactory operation. A sharp pressure spike is often observed in spite of the decoupling and seems to be due to an enhanced heat transfer ratio when the temperature of the system goes through the transformed critical line. This may be due to a transition from film to nucleate boiling as the system drops in temperature.

A crude calculation of pressure rise for the low-frequency oscillations was made by assuming the mass flow to be determined by the entrance impedance to the warm section, with the liquid vapor interface moving as a front and the vapor generation rate controlled by convective film heat transfer over the interface. The pressure rise lags in time owing to the line capacity, and can overshoot the supply pressure if the vaporization rate exceeds the mass flow escaping the system through the downstream impedance. As soon as the downstream pressure exceeds the supply pressure, reverse flow occurs, since the inertia of the hydrogen flow is very low. If the supply has a complicated transfer function arising from dynamic control elements or a turbopump, coupled oscillations of large amplitude are apt to arise between the supply system and the flow system.

A much more detailed calculation on a single transfer line has been made by W. Gene Steward¹⁵ with excellent agreement obtained for the pressure rise during the first half-cycle.

Compact, low-mass systems such as the feed system for a nuclear rocket propulsion engine should be well behaved if the above conclusions are correct. The addition of turbulator strips should stabilize heat transfer characteristics for large systems and make their performance more predictable.

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