WATER FILM COOLING OF AERODYNAMICALLY HEATED BODIES

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ABSTRACT

An experimental investigation on the film cooling of blunt bodies has been carried out, using water as a coolant.

The investigations have been performed in three phases. The first of these was a study of the film-coolant properties on a blunt body exposed to a supersonic gas stream. The second covered a photographic study of surface irregularities on a water film. In the third phase a method was developed for the study of the velocity distribution in thin water films (<1 mm).

INTRODUCTION

Hypersonic vehicles are exposed to considerable heating at the stagnation points. Several cooling methods have been suggested—for example, film, transpiration, and ablation cooling. Of these the last mentioned has been utilized in many reentry applications. For aerodynamic bodies where there is a demand for a conserved body shape, ablation cooling is not suitable. Transpiration cooling offers many interesting possibilities; several difficulties, however, are encountered. In certain areas film cooling has the greatest advantages.

At the research department of Svenska Flygmotor (SFA) an investigation of the film cooling of blunt bodies was initiated in 1961 under a contract from Svenska Aeroplan AB (SAAB). In all experiments, water has been used as the coolant. The test models have been of two types, with central and with peripherical injection. In both cases the diameter of the models was 30 mm.

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The investigations performed can be divided into three groups:

1. Tests at Mach 3.1, in a 2350°K rocket exhaust with central injection model.
2. Tests at Mach 2.4, in a cool wind tunnel with peripheral injection model.
3. Study of a method to measure film thickness and velocity distribution in a water film.

The main objective for the group 1 tests was to obtain a measure of the effective coolant length and the coolant requirements for certain arrangements.

The group 2 tests consisted of a photographic study of water films. Observations of the irregular water surface was made. The last part of the work was concentrated on the development of a method by which the velocity distributions in thin water films (0.1–1 mm) could be measured.

LITERATURE REVIEW

During the past fifteen years a large number of papers on liquid film cooling and related problems have been published. References 1 and 12 may be consulted if a more complete literature list is required.

The reported experimental work can be divided broadly into two groups, one which concerns film cooling applied to the inside of a (motor chamber) tube—no main flow pressure gradient—and one where pressure gradients exist (blunt-body and nozzle cooling). It is then found that by far the most work is done on the first group.

A division of the published material may also be done along the following lines:

(a) Heat-transfer characteristics
(b) Stability limits
(c) Injection characteristics

Most of the reported investigations are of the first type [1–3, 6, 7, 9–11, 13]; Crocco's paper [2] which is an extension of a previous paper by Rannie, gives a theoretical analysis of the heat-transfer characteristics, including the case of an injected reactant fluid. In some of the above-mentioned papers, experimental evidence of the unstable behaviour of the film under certain conditions is given—e.g., the paper by Kinney, Abramson, and Sloop. Theoretical calculations on the film stability are presented in the papers by Feldman [15] and Anliker-Beam [16]. One of the papers listed here [5] is devoted mainly to the investigation of the injection mechanism.

The technique used in most of the heat-transfer measurements consists of measuring the temperature of the liquid-cooled wall. From this temperature the heat transfer through the film is then calculated. Correlations may be obtained between the coolant flow and the hot-gas flow which enable one to calculate the necessary coolant rate for a given case [1]. It is also possible to determine the "coolant length," that is, the length that is covered with liquid for a given liquid-flow rate [7]. The temperatures have in one case [8] been used for an indirect determination of the film thickness.

When heat-transfer determinations based upon wall temperature measurements are made, it is most often assumed that the water surface immediately after leaving the injector slot attains a temperature near the boiling point. This is, however, not always the case. If the water has an initial temperature around 20°C, the time τ_e needed for the surface to reach boiling conditions may be comparable to the total flow time from the injector to the end of the test section. Solutions of the heat conduction equation with integral methods have shown that the time τ_e is given by the following relation:

$$\tau_e = \eta^2 \frac{\lambda^2}{\alpha^2} \frac{4}{5\kappa}$$

where η = temperature ratio $(T_s - T_i)/(T_g - T_s)$
T_s = surface temperature
T_i = initial liquid temperature
T_g = surrounding gas temperature
λ = the liquid thermal conductivity
α = gas heat-transfer coefficient
κ = thermal diffusivity of the water

The temperature ratio may be of the order of 0.1, while α is of the order of 100–1000 watts/m² °K in most of the experiments reported. Calculated time delays are of the order of 0.02–0.2 sec. In most cases the liquid film velocity is of the order of 0.1 to 1 m/sec which in turn means that the delay length may vary between a few centimeters up to half a meter. Obviously this effect cannot be neglected when discussing, for instance, the results given in Ref. 8.

The behaviour of the liquid film is of great importance for an effective use of the coolant. Kinney reports that for Reynolds number over about 200 (with film thickness as characteristic length) the film becomes unstable. Wave formations occur with loss of liquid drops from the wave crests as a result. These losses may considerably reduce the heat-shield capacity of a certain liquid flow.

EXPERIMENTS IN ROCKET EXHAUSTS

The aim of the first part of the experimental investigation carried out at Svenska Flygmotor was to determine the coolant efficiency of a water film on a blunt body at supersonic conditions. Due to the experimental complexities it was decided not to use thermocouples as heat-transfer sensors on the blunt body. Instead it was thought that by using a body made of an ablating material the body itself would serve as a (heat-transfer) sensor. The parts of the body which were not protected by the water film (and thus exposed to the hot gas) would ablate and an approximate measurement of the film-cooled length would then be possible by studying the ablation marks after the test.

For the generation of hot gas a liquid-propellant rocket motor burning methanol and hydrogen peroxide was used. The combustion products were roughly 5 parts H_2O and 1 part CO_2. Most of the tests were run at stoichiometric conditions. The calculated flame temperature was found to be around $2500°K$ at a chamber pressure of 45 atmospheres. The real gas temperature in the gas stream core obtained in the experiments was, however, 100–200° lower according to thrust measurements. The deficiency was probably caused by incomplete combustion.

The test body was mounted on a sting which could be pivoted from a position outside the gas stream to a position along the rocket motor axis. The sting was separately water cooled.

Figure 1 shows the general appearance of the experimental equipment. The nozzle was profiled to parabolic shape in order to give axisymmetric flow. Combustion chamber and nozzle were regeneratively cooled with liquid hydrogen peroxide.

The Mach number at the nozzle exit was 3.1. Teflon was chosen as the test-body material because of its suitable ablation characteristics. Tests were performed with bodies of two different total lengths, 90 mm and 45 mm. All test bodies were spherically rounded cylinders with the diameter equal to 30 mm. In most of the tests the body was exposed to the hot gases for 15 sec. Some of the tests with low water mass flow were limited to 10-sec runs because of the considerable ablation of the test specimens. After each test the ablation weight loss was measured and visual observations of the irregular surface structure were made. Such irregularities could be caused by particle impingment which might lead to transition in the laminar water film. Also, the natural instability of the water film played a very significant role.

The water mass flow was varied between 20 g/sec up to 90 g/sec. The Reynolds numbers on the cylindrical portion of the test specimens (with the film thickness as reference length) were accordingly 400 and 1800. This is in the regime were instabilities are to be expected [1].

The main objects of the tests were to determine the necessary water mass flow to obtain a complete heat shield of a 90-mm test specimen. By diminishing the water flow to values under this critical flow rate it was also possible to obtain an indirect relationship between water flow rate and cooled length. The latter was not obtained explicitly, but instead the parameter was the total rate of ablation of Teflon, which is inversely related to the cooled length. In Fig. 2 the ablation weight loss (in grams/sec) is shown plotted as a function of the water mass flow. The five points
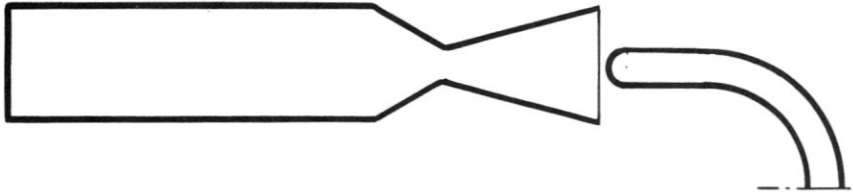
Figure 1.   Experimental equipment for tests in rocket exhaust.
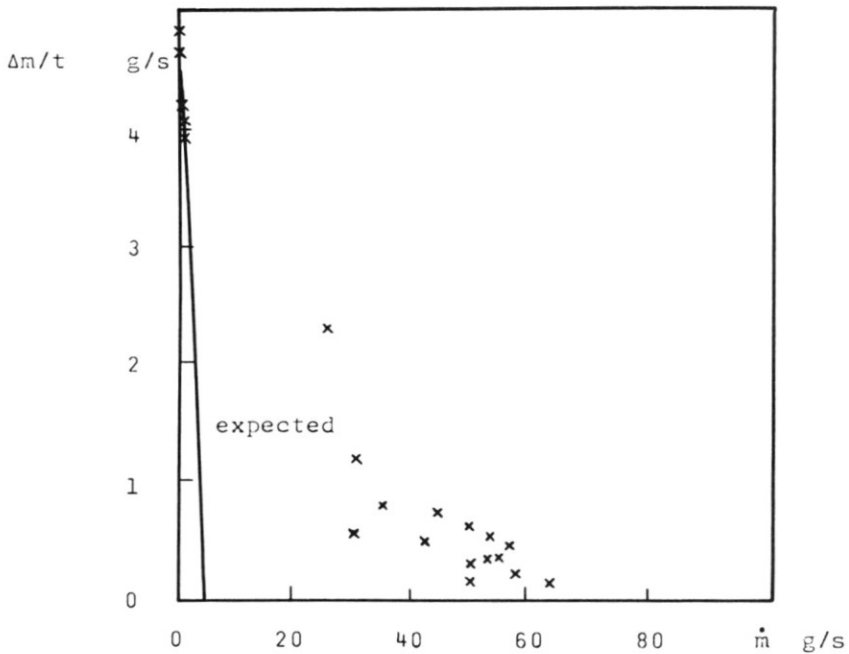

Figure 2.   Ablation of test body as function of water film flow.

on the ablation mass flow axis were obtained with special test specimens without water injection.

From this diagram it was found that the quantity of water needed to cool the surface of the test body ($\sim$90 cm^2) was around 45 g/sec, that is, roughly 0.5 g/cm^2/sec. This is a rather large figure in view of the fact that the amount of Teflon which is ablated from the same uncooled surface is only 4.5 g/sec. Thus it seems that Teflon is some ten times as efficient as water as a heat shield for this specimen! However, if one compares the heats of ablation at these conditions it is found that they are equal to within a few percent. In other words, if the water film behaved perfectly, the amount of water needed to protect the surface would have been only 4.5 g/sec instead of the measured amount 45 g/sec (compare filled line in figure).

The heat of ablation of Teflon could be calculated from the measured values of the ablation rate at the stagnation point. The resulting value, 5.4×10^6 J/kg at a boundary layer enthalpy difference of 4.5×10^6 J/kg, agrees very well with published data.

The main conclusion drawn at this point of the investigation was that the film-cooling efficiency depended overwhelmingly on the stability of the film and not on the heat fluxes encountered on the film surface. It was therefore decided to direct further efforts towards an investigation of the mechanical behaviour of the liquid film.

The aims of the continued investigation are summarized below.

1. Photographic study of the water film in order to obtain an overall picture of the film behaviour.
2. Measurement of mean film velocity and thickness.
3. Measurement of the velocity distribution in the film.

It was decided that part of these investigations should be performed in the jet from a cool-air nozzle to avoid complications from hot glowing gases. The Mach number at the exit of the nozzle was 2.35 and the free stream temperature of the air only 129°K. A large part of the experiments under (2) and (3) have been carried out in two-dimensional channels at subsonic conditions.

The photograph in Fig. 3 was taken using a test body with water injection through a circumferential slit on the cylindrical part. The picture is magnified five times. The irregular profile of the water film is clearly observed and one can also see the misty parts which demonstrate the tearing off of water droplets.

From pictures similar to this one it was possible to estimate the film thickness. It was found to be less than 1 mm. Obviously the measurement of film velocity profiles and stability characteristics was impossible using
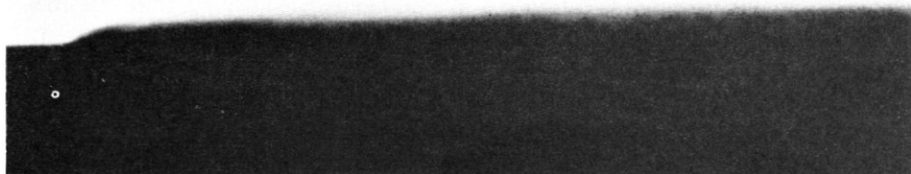
Figure 3. Shadow photograph of water film.

conventional probes. A new technique was therefore developed using small metal particles mixed with the water film. The film is photographed with a camera of known exposure time (1–10 millisec) and on a series of pictures a large number of traces can be observed, and their corresponding velocities measured. When, say, 500 traces are obtained, a distribution diagram of the number of traces as a function of their velocities is drawn. Two assumptions are then made:

(a) The particles are uniformly distributed through the film thickness photographed.
(b) The velocity profile is monotonic.

The distribution diagram is then easily converted into a velocity profile. The mean film thickness and velocity are also obtained.

This method has been applied to water films of thicknesses from 0.1 mm up to 1 mm. The particles used should not be greater than, say, $\frac{1}{10}$ the film thickness. There are also limitations of the particle size which depend on the origin of velocity lags between particles and the water flow. A calculation of the limiting particle size has shown that for films velocities up to a few meters per second the particle size should not exceed 100 μm.

Another limitation to the technique may arise from the fact that the small water droplets which are formed at the water surface at unstable conditions may reflect the incident light and thus give rise to traces on the picture which interact with the particle traces.

The particle experiments were performed partly in a two-dimensional horizontal glass channel 50 × 50 mm and partly on the cylindrical model with the circumferential slot. The injector formed in both cases a 45-degree angle with the axis and had a variable opening. Only room temperature tests were made. The velocity of the cocurrent air was varied between zero and 50 m/sec. Besides the velocity determinations, observations of surface instabilities were made.

The diagram in Fig. 4 shows the similarity of velocity profiles obtained at different locations downstream of the slot as functions of dimensionless thickness. The latter is obtained by dividing the coordinate with the actual thickness. The Reynolds number is 92 and the slot width is 1 mm. Figures in the diagram refer to the distance of the location from the slot. Cocurrent air flow was zero.

The influence of the Reynolds number on the velocity profiles is shown in Fig. 5. These profiles were measured without air flow.

In Fig. 6 is shown the influence of a cocurrent air flow on a water film. The mean film velocity is of the order of 10 cm/sec. Coordinates are velocity and distance from the wall. The slot width was 0.40 mm.
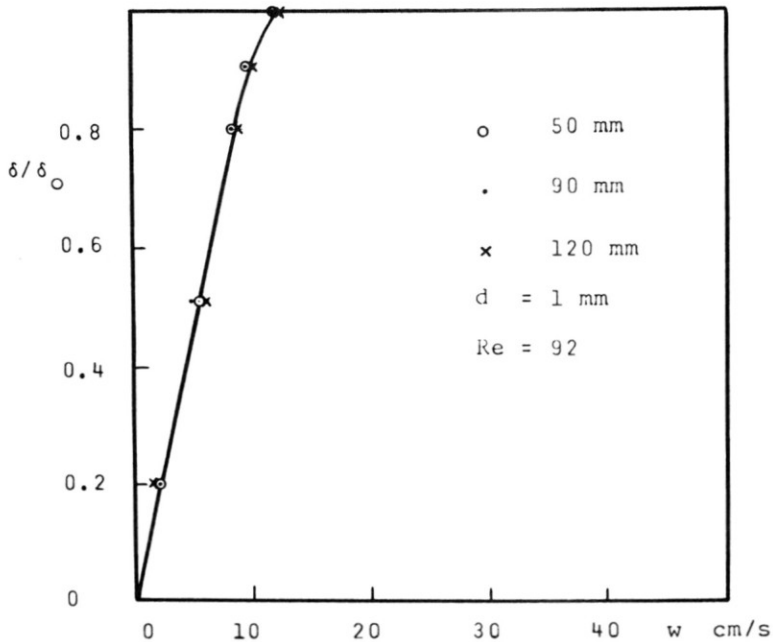

Figure 4.   Velocity profiles in water film at different locations downstream of slot.
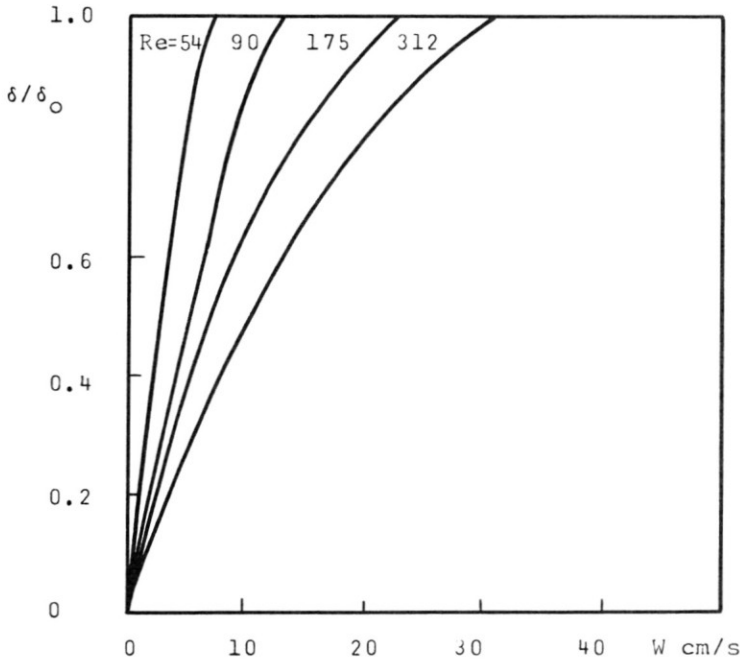
Figure 5.   Influence of Reynolds number on velocity profiles.
With cocurrent air flow.

Experiments with water films with mean velocities of the order of 1 m/sec showed that velocity profiles obtained at air flows of 30 m/sec are practically identical to profiles obtained at no air flow conditions (Fig. 7). There are also no differences in thickness within the limits of experimental error.

This behaviour may be explained in the following way. The quantity density $\times$ (velocity)^2 may be referred to as a measure of the shear stress to which a volume element is exposed when moving through the film. When this quantity at the boundary between the two media is greater on the liquid side than on the air side, it is not likely that the air flow will influence the film profile or thickness. This is the case in the above-mentioned experiment with the high speed water film where ρw^2 in the liquid at the upper surface is approximately five times ρw^2 in the cocurrent air. The low speed film has on the contrary a ρw^2 which is only one tenth of that of the air flow.

Two types of instabilities have been observed. One is an inherent water film instability in the form of surface waves which may be observed on films with no cocurrent air flow. The other type is induced by the air flow.

Both types have been observed at rather low water film Reynolds numbers (of the order of 300 and 100 respectively). The observation that the critical Reynolds number for the induced instability may be as low as 100 is in contradiction with statements made by Hermann [10]. The following photograph (Fig. 8) shows typical induced instabilities on a water film at Re = 90 and a low mean film speed with a cocurrent air flow of 5 m/sec. The same water film, without air flow, is perfectly smooth.

In experiments with higher film velocities (1 m/sec) the induced instabilities were observed first at air velocities of the order of 50 m/sec. Increasing the air velocities above the value at which instabilities occur leads in both cases to a complete destruction of the water film.
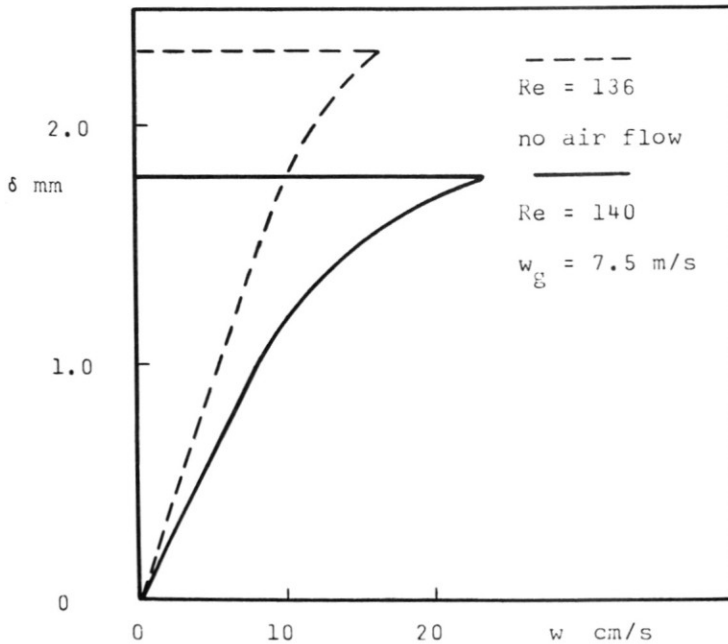

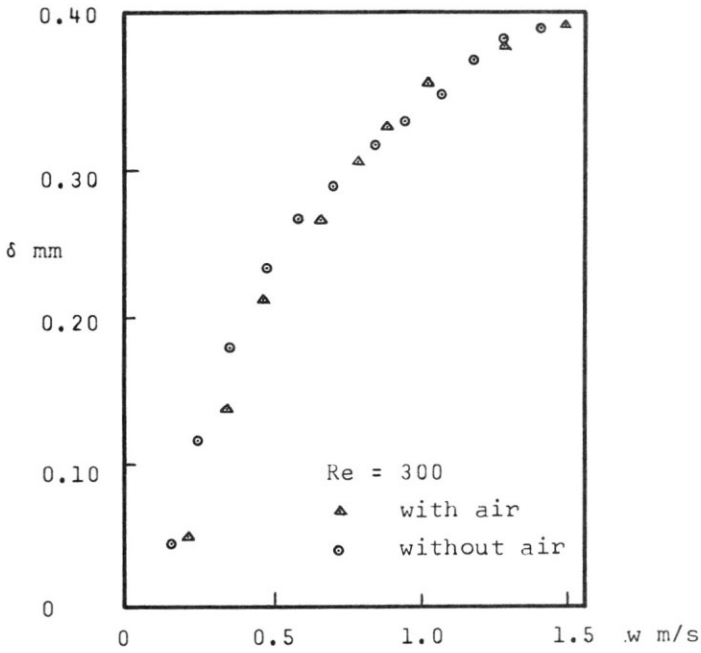Figure 6.   Influence of cocurrent air flow on a slow water film.

Figure 7. Velocity profiles of a rapid water film with and without cocurrent air flow.
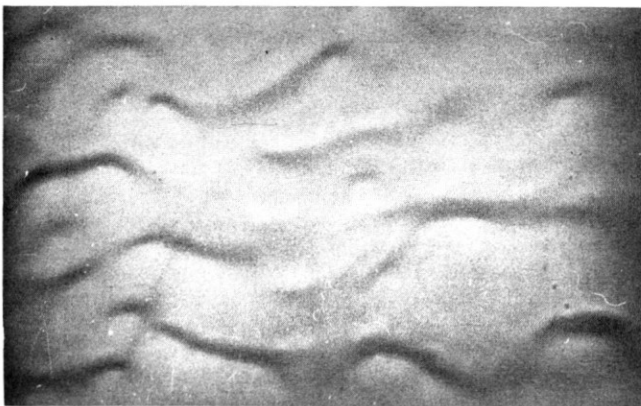

Figure 8. Surface instabilities on a slow water film (Re = 90) with cocurrent air flow (7,5 m/s).

CONCLUSIONS

The main problem in liquid film cooling applications is to keep the film stable. To obtain this it is necessary to keep the film Reynolds number low—say, under 300. The liquid flow rate from a given slot is thus limited and a close spacing between slots in a certain design may be the solution, if this criterion is applied. Further, the film velocity has to be high enough to avoid induced instabilities. This makes demands on the design of the injector. Obviously, simple injectors using holes through which water pours at right angles to the air flow are not very well suited to this condition.

The reported investigations may be regarded as preliminary. Further studies of the mechanics of a coolant liquid film are needed before satisfactory design criteria are obtained.

REFERENCES

1. Kinney-Abramson-Sloop, "Internal-Liquid-Film-Cooling Experiments with Airstream Temperatures to 2000°F in 2- and 4-Inch-Diameter Horizontal Tubes," NACA Report 1087.

2. Crocco, L., "An Approximate Theory of Porous, Sweat, or Film Cooling with Reactive Fluids," *J. Am. Rocket Soc.*, vol. 22, no. 6 (1952).

3. Knuth, E., "The Mechanics of Film Cooling," *Jet Propulsion*, vol. 24, no. 6 (1954) and vol. 25, no 1 (1955).

4. Greenberg, A., Discussion of "The Mechanics of Film Cooling for Rocket Motors," *Am. Rocket Soc.*, Fall meeting preprint 313–56 (Sept. 1956), pp. 24–26.

5. Warner-Reese, "Investigation of the Factors Affecting the Attachment of a Liquid Film to a Solid Surface," *Am. Rocket Soc.*, Fall meeting (Sept. 24–26, 1956), also *Jet Propulsion*, vol. 27, no. 8 (1957).

6. Sellers, J. P., "Experimental and Theoretical Study of the Application of Film Cooling to a Cylindrical Rocket Thrust Chamber," Ph.D. thesis, Purdue University (1958).

7. Zucrow-Sellers, "Experimental Investigation of Rocket Motor Film Cooling," *ARS J.* (May 1961).

8. Polyavev, V. N., "Experimental Investigation of the Flow of a Vaporized Liquid Film along the Surface of a Cone Blown by Gas," translation from *I.U.U.Z. Mach.* No. 5, AD 287701 (1960), pp. 140–148.

9. Norman-McIntyre, "Heat Transfer to a Liquid Film on a Vertical Surface," *Trans. Inst. Chem. Eng.*, vol. 38 (1960).

10. Hermann, R., "Evaporative Film Cooling of Blunt Bodies in Hypersonic Flow and Its Application to Re-entry Vehicles," XIth International Astronautical Congress, Stockholm (1960).

11. Hermann-Melnik, "Evaporative Film Cooling at Hypersonic Velocities for Re-entry Vehicles," Univ. of Minnesota, Institute of Technology, AD 286 173 (April 1961).

12. Hyman et al., "Transpiration and Film Cooling for Solid Propellant Rocket Nozzles," United Nuclear Corporation, AD 273 333 (Feb. 7, 1961).

13. Emmons-Warner, "Effects of Selected Gas Stream Parameters and Coolant Physical Properties on Liquid Film Cooling," Jet Propulsion Center, Purdue Univ., AD 277 072 (January 1962).
14. Sellers, J. P., "An Application of Photography in Film-Cooling Research," *ARS J.*, vol. 32, no. 8 (1962).
15. Feldman, S., "On the Hydrodynamic Stability of Two Viscous Incompressible Fluids in Parallel Uniform Shearing Motion," *J. Fluid Mech.* (June 1957).
16. Anliker-Beam, "On the Stability of Liquid Layers Spread over Simple Curved Bodies," *J.A.S.* (October 1962).

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