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The Mechanics of Film Cooling[1]—Part 1

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Thin liquid wall films flowing under the influence of high-velocity turbulent gas streams were studied for the purpose of obtaining an understanding of the mechanics of film cooling. Conditions which insure liquid-film attachment to solid surfaces without loss of unevaporated liquid to the gas stream when simple radial-hole injectors are used were found; the maximum allowable coolant-flow rate for a stable coolant film was determined (a stable coolant film is obtained when no unevaporated coolant is entrained by the gas stream as the result of interfacial disturbances); and a method for calculating the evaporation rate and the surface temperature for a stable inert coolant film was found.

Nomenclature

a = velocity of sound
c_p = specific heat at constant pressure
Ca = modified cavitation parameter
C_f = gas-stream friction coefficient
C_h = gas-stream, heat-transfer coefficient
C_m = gas-stream, mass-transfer coefficient
d = duct diameter
D = molecular mass diffusivity
f = evaporation coefficient
H = enthalpy
ΔH = coolant heat of vaporization
k = thermal conductivity
L = liquid-film or test-section length
$\dot{m}$ = mass transfer per unit area and per unit time
p = pressure
Pr = Prandtl number
$\dot{q}$ = heat transfer per unit area and per unit time by conduction
r = distance from the center line of the pipe
R = gas constant
Re = Reynolds number
Sc = Schmidt number
T = temperature
u = velocity in the x-direction
u^* = $u/\sqrt{\tau_0/\rho_0}$
v = velocity in the y-direction
V = liquid velocity averaged over cross-sectional area of injection orifices
= oxidizer transfer per unit area and per unit time
y = distance into gas stream from gas-stream bounding surface measured perpendicularly to bounding surface
y^* = $\rho_0\sqrt{\tau_0/\rho_0}\, y/\mu_0$
Γ = liquid flow per unit time and per unit length of tube circumference
δ = gas-stream laminar sublayer thickness
δ' = $\int_0^\delta (\mu_{M0}/\mu_M)\, dy$
δ^* = $\rho_\infty\sqrt{\tau\delta/\rho_\infty} \int_0^\delta (1/\mu_M)\, dy$
η = film thickness averaged with respect to x and t
η^* = $\rho_{Lf}\sqrt{\tau_0/\rho_{Lf}}\eta/\mu_{Lf} \approx \sqrt{2\Gamma}/\mu_{Lf}$
θ = oxidizer specific concentration (weight of oxidizer per unit total weight)
μ = dynamic viscosity
π = 3.14
ρ = density
τ = shearing stress

Subscripts

G = gas
Lf = liquid in the film
Li = liquid in the injector orifice
M = mixture of gas and vapor
0 = bounding surface of gas stream (a liquid film surface or a duct wall)
s = saturation conditions corresponding to T_0
t = total
V = vapor
δ = junction of turbulent core and laminar sublayer in gas stream
∞ = bulk property or average velocity

1 Introduction

FILM cooling[3] is the protection of a given surface from injurious effects of a proximate heated fluid stream by the interposing of a thin continuous protective liquid film between the given surface and the fluid stream. Its use is justified when the proximate fluid stream is extremely hot and when a more satisfactory method for protecting the given surface from destruction by heat is not available; or when the proximate fluid stream reacts chemically with the given surface, when such chemical reaction is undesirable, and when a more satis-

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[3] Although the flow of the thin liquid wall films under the influence of high-velocity turbulent gas streams and/or the unidirectional turbulent diffusion of one gas through another gas occurs in numerous engineering applications (e.g., in evaporators, condensers, two-phase combustion processes, and film-cooling systems), attention will be concentrated, for the sake of convenience, on that application which motivated the present study—film-cooling systems.

factory method for separating the injurious fluid stream from the given surface is not available; or when the proximate fluid stream carries with it materials which are deposited easily on solid surfaces and when deposits of this nature are undesirable on the given surface. Structural members which are likely to be film-cooled include combustion chambers,[4] where the heated fluids are the products of combustion, and external surfaces of high-velocity missiles, where the heated fluids are aerodynamically heated atmospheric gases. Inability to cool these structural members adequately could limit seriously the performance of the corresponding machines.

The benefits of film cooling are realized most fully when the liquid film is attached to the surface without loss of unevaporated liquid to the proximate fluid stream, when the attached liquid film is stable (i.e., no unevaporated liquid is lost to the proximate fluid stream as the result of disturbances on the film surface), and when the evaporation rate is low.[5] It is important, therefore, to know how these three conditions may be obtained. Little basic information was available in 1950, however, regarding the prerequisites for these conditions. Consequently, a study was initiated during that year for the purpose of obtaining a basic understanding of thin liquid wall films flowing under the influence of high-velocity turbulent gas streams by investigating the attachment of liquid films to solid surfaces in the presence of high-velocity gas streams, the conditions which are sufficient for stability of liquid wall films flowing under the influence of high-velocity turbulent gas streams, and the rate of evaporation from a stable liquid wall film into a heated turbulent gas stream. The results of that study (2)[6] are summarized in this paper.

2 Experimental Equipment

A Equipment for Film-Attachment Studies

The flow diagram for the equipment used in the film-attachment studies (4) is presented in Fig. 1. The equipment consisted essentially of an air-supply system, a liquid-supply system, a Lucite test section, and appropriate controlling and measuring devices.

The air was obtained from the standard air-supply system in general use at the Jet Propulsion Laboratory; its flow rate was measured with the aid of a sharp-edge orifice which had been designed according to ISA specifications, a 30-in. mercury manometer, a Bourdon-type pressure gage, and an iron-constantan thermocouple. After being passed through the measuring orifice, the air was conducted through the Lucite test section (located 46 diameters downstream from the measuring orifice) and exhausted to the atmosphere through a manually operated gate valve (located 16 diameters downstream from the test section). The magnitude of the static air pressure in the test section, which was controlled by the gate valve, was measured with a Bourdon-type pressure gage, and the air temperature in the test section was measured with the aid of an iron-constantan thermocouple.

The liquid used in the tests was stored in a metal tank pressurized by nitrogen gas from a commercial compressed-nitrogen bottle. From the storage tank the liquid was conducted through a rotameter, a manually operated needle valve, a screen filter, and finally into the test section through one of the four available injector openings. The liquid temperature was measured at a point several inches upstream from the injector with the aid of an iron-constantan thermocouple; electric potentials from the thermocouples were measured with the aid of a hand-balanced potentiometer.

The Lucite test section was fabricated from commercially available stock having a 3-in. inside diameter and a $^1/_4$-in. wall thickness. Lucite was selected because of its transparency and good machining properties. Four radial holes, ranging from $^1/_{16}$ to $^5/_{32}$ in. in diameter, were drilled at 90-deg intervals around the periphery of the test section. During any given test, liquid was injected through only one of these holes; the other holes were utilized as static-pressure taps and thermocouple sites.

A total-pressure probe attached to a manually operated micrometer screw was used for the purpose of investigating the velocity profile of the air flowing in the test section. Tests were conducted only after the velocity profile was found to be symmetric with respect to the center line of the duct.

B Equipment for Film-Stability and Evaporation-Rate Studies

The flow diagram for the equipment used in the film-stability and evaporation-rate studies is presented in Fig. 2. The equipment consisted essentially of a gas-supply system, a liquid-supply system, several interchangeable test sections, and appropriate controlling and measuring devices.

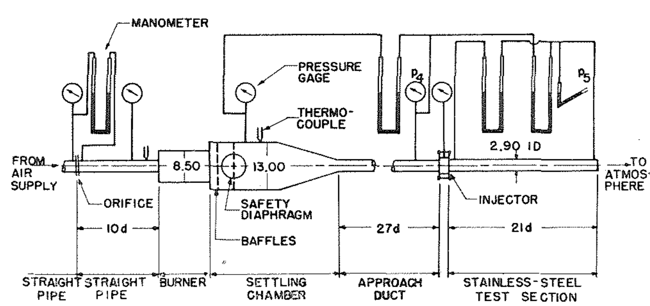

Fig. 2 Flow diagram for equipment used in research on stability of and evaporation from liquid wall films

The gas was in general produced by burning fuel (Union Oil Company's No. 1 thinner) and air in a modified turbojet combustion can. The fuel flowed into the burner from a nitrogen-pressurized storage tank; its flow rate was measured with the aid of Bourdon-type pressure gages and a calibrated injection nozzle. The air was obtained from the standard air-supply system in general use at the Jet Propulsion Laboratory; its flow rate was measured with the aid of a sharp-edge orifice which had been designed according to ISA specifications, a 50-in. mercury manometer, a Bourdon-type pressure gage, and a chromel-alumel thermocouple. The products of combustion were mixed and then calmed in an insulating settling chamber having a cross-sectional area eighteen times that of the approach duct. After passing through the settling chamber, the combustion products flowed first through

[4] Historial Note: It is believed that credit for the first application of film cooling is due Robert H. Goddard, pioneer of rocketry in America, who is known to have film-cooled the combustion-chamber walls of experimental rocket motors in the year 1929 (Ref. 1, p. 3).

[5] If the given surface is the inner wall of a rocket motor, it is desirable also that the liquid be reactive with the combustion products, thereby acting, at least to some extent, as an injected propellant as well as a film coolant; that the liquid be one of the propellants, so that no special supply system is required for the coolant; and that an inexpensive, noncritical, light-weight material (perhaps aluminum; see Ref. 3) be used in the construction of the combustion-chamber wall.

[6] Numbers in parentheses refer to References on page 365.

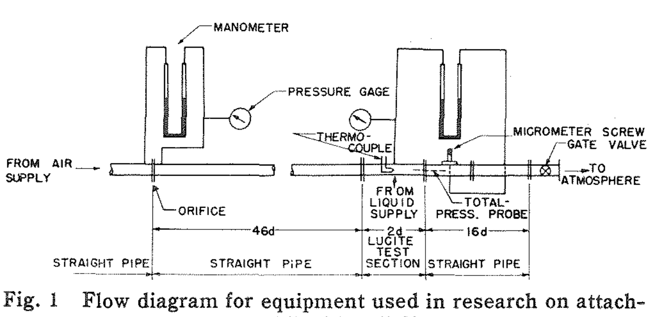

Fig. 1 Flow diagram for equipment used in research on attachment of liquid wall films

27 diameters of insulated, straight, constant-diameter approach duct and then into the test section. The total gas temperature in the settling chamber was measured with the aid of a shielded chromel-alumel thermocouple; the magnitude of the static pressure in the approach section immediately upstream from the injector was measured with a Bourdon-type pressure gage; and the pressure drop in the test section was measured with the aid of a 50-in. water manometer.

Water (procured directly from the Laboratory water supply pipe at approximately 100 psig) and aqueous sucrose solutions (produced by mixing tap water and reagent sucrose and stored in a nitrogen-pressurized supply tank) constituted the liquids in the film-stability tests; water was the only liquid used in the evaporation-rate tests. After leaving the Laboratory water-supply line (or the supply tank, as the case may be), the liquid flowed (in the sequence named) through one of two manually operated needle valves, one of two rotameters, a filter, the coolant-injector plenum chamber (Fig. 3), twenty-four (twelve, for one group of tests) 0.011-in.-square passages (characterized by relatively high flow resistances and serving to nullify gravity effects in the plenum chamber), and corresponding equally spaced, $^1/_{16}$-in.-diameter, radial-injection holes. The liquid was attached to the inner wall of the test section by the action of the high-velocity gas stream. For tests employing unheated gases, the film temperature was assumed to be equal to the wet-bulb temperature in the case of a water film and the temperature (measured) of the exhausted liquid in the case of a film of aqueous sucrose solution; for tests employing heated gases, the film temperature was calculated using Equation [39] of this paper.

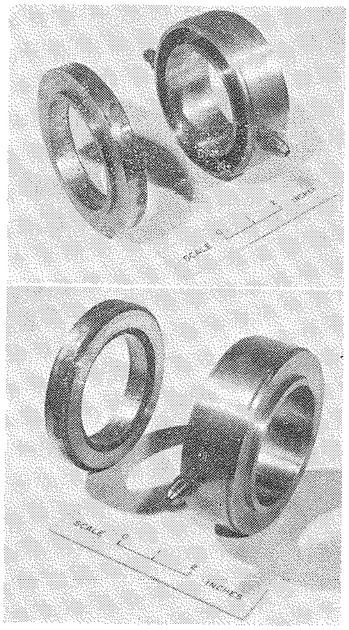

Fig. 3 Views of the coolant injector used in research on liquid wall films

For use in tests employing heated gases, a test section was fabricated from a 5-ft length of 347 stainless-steel tubing having a 0.063-in. wall and a 3-in. outside diameter. The inside diameter of the tube was honed to 2.90 in. (leaving a wall thickness of 0.050 in.), and 120 thermocouples were spot-welded to the outside of the tube, one every inch (measured axially) at the 12 o'clock position and one every 3 in. at the 3, 6, and 9 o'clock positions. For use in tests employing gases at ambient temperature, several lengths of Lucite tubing having a 3-in. inside diameter and a 0.25-in. wall were procured.

The electric potentials from the thermocouples which were used in order to facilitate the measurement of the gas temperature and eight of the test-section-wall temperatures were recorded on a 12-point, 50-mv-range Brown recorder located in the control room. The remaining 112 thermocouples were connected in turn to a continuously recording, single-channel potentiometer located at the central recording room of the Jet Propulsion Laboratory by means of a 25-point, 10-level, telephone-type automatic electric stepping switch capable of scanning the 112 thermocouples in less than 2 min.

3 Liquid-Film Attachment With Radial Injector Holes and a High-Velocity Gas Stream

A Previous Studies

Previous systematic studies of the liquid-film-attachment problem were limited to the experimental determination of the critical velocity of injection when a slot around the duct circumference is used (5, 6, 7), where the critical velocity of injection was defined as the maximum mean velocity of the liquid in the injection slot obtainable with no visible separation of the liquid film from the inner surface of the test section. The authors of these papers asserted that the use of injection slots would provide more uniform liquid films and more easily controlled liquid-flow rates than could be obtained with other film-attachment methods. Remarks on these assertions will be made in the following sections 3-C and 4-B.

B Experimental Results

An experimental study was conducted in order to determine the critical velocity of injection for attachment of a liquid film to the inside of a circular duct when radial injector holes and effects of a high-velocity gas stream are used (4). The critical velocity of injection was defined as the maximum mean velocity of the liquid in the injector orifices obtained with no visible separation of the coolant film from the inner surface of the test section.

Liquid viscosities from 1.59×10^{-5} to 10.69×10^{-5} lb sec/ft^2, liquid densities from 1.94 to 3.02 slugs/ft^3, and liquid vapor pressures from 0.15 to 3.85 psia were secured by using water, aqueous zinc chloride solutions, aqueous sucrose solutions, and carbon tetrachloride. Test-section air densities from 2.26 to 9.58×10^{-3} slug/ft^3 were provided by a gate valve at the discharge end of the air duct; no other appreciable gas-property variations were realized. Injector-orifice diameters varying from $^1/_{16}$ to $^5/_{32}$ in. were achieved by using different injectors; no gas-duct-diameter variations were realized.

For each test point, the air-supply system was operated at the desired output until a stable air-flow rate was obtained. When this condition was realized, the liquid-flow rate was increased slowly from the no-flow value to a value when the critical velocity of injection was reached. At that instant the air-flow rate, the injected-liquid-flow rate, and the appropriate temperatures and pressures were recorded. The data taken at the critical injection velocity are given in Table I of Ref. 4.

Incidental to the obtainment of attachment data, the circumferential spread of the liquid film corresponding to liquid flows at 21 different critical injection velocities was measured at a point located arbitrarily 1.25 in. downstream from the injection point. The spread appeared to be chiefly a function of the liquid-flow rate; i.e., the fluid properties, the air velocity, and the injector-hole diameter had apparently a minor effect on the spread for the range of fluid properties and air velocities tested. Typical values of the spread were 0.75 in. for 1.5×10^{-4} slug/sec and 1.50 in. for 6.0×10^{-4} slug/sec of liquid flow. Since the spread would vanish as the liquid-flow rate approached zero, the data would seem to indicate that the circumferential spread is proportional to the square root of the liquid-flow rate.

C Discussion of Data

Since no theoretical analysis of the film-attachment problem has been made, the data were plotted in dimensionless form (Fig. 4); the abscissa is a function of gas-stream Reynolds number Re_G, liquid-stream Reynolds number Re_{Li}, and a modified cavitation parameter Ca_{Li}, and the ordinate is the ratio of the gas- and liquid-stream momenta $\rho_\infty u_\infty^2/\rho_{Li}V^2$. Here Re is Reynolds number based on diameter, Ca is a modified cavitation parameter defined by $Ca = \rho_{Li}V^2/(p - p_V)$, p is pressure, V is liquid velocity averaged over the cross-sectional area of the injection orifices, and the subscripts G, Li, and V refer to gas, liquid in the injector orifice, and vapor, respectively. The exponents of the dimensionless parameters were determined from crossplots on log-log paper of liquid- and gas-stream parameters for a constant value of the momentum ratio. (The line drawn in Fig. 4 has a scope of 0.8.) The dimensionless parameters used are speculative to the extent that the gas viscosity and test-section diameter were held constant and the vapor pressure of the liquid was varied over only a small range during the tests; e.g., with available data it was not possible to discern whether the significant gas-stream Reynolds number is that (based on gas velocity u_∞) which describes the gas stream in general or that (based on friction velocity $\sqrt{\tau_0/\rho_0}$) which describes only the gas flow near the duct wall.

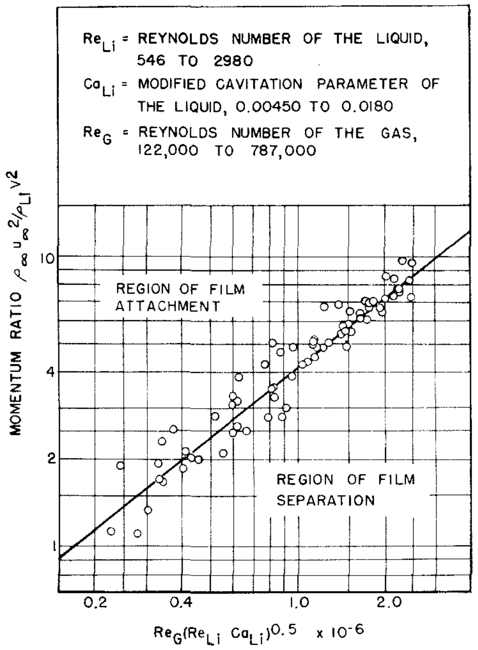

Fig. 4 Dimensionless plot of film-attachment data taken at critical velocity of injection

It is concluded that effective film attachment may be obtained with simple radial-hole injectors in the presence of a high-velocity gas stream over a useful range of operating conditions so that the study of more complex means of injection (such as porous walls and circumferential slots) and of insuring film attachment probably is not required. It is concluded furthermore that the critical velocity of injection is a definite function of certain parameters of the system; thus it is possible to predict beforehand whether a given film-coolant stream will attach to the wall or will continue on into the gas stream.

Fig. 4 should be a useful guide in the design of film-cooling systems for turbulent flat-plate flows as well as for turbulent duct flows. Until further information is obtained, it is suggested that twice the local boundary-layer thickness be taken to be the characteristic gas-stream dimension in the case of flat-plate flows; this dimension corresponds to the duct diameter which was used in the case of pipe flows. Obviously, caution should be exercised when extending the presented results to parameter values outside the investigated range.

Since the calculation of streamlines for viscous fluid flows around sharp corners is an extremely difficult task, it seems unlikely that an analytical study of the film-attachment problem would be a rewarding undertaking at the present time. Experimental methods, on the other hand, have already been used successfully for the determination of the relative importance of several parameters involved in the film-attachment process. Therefore, if it should be deemed necessary to obtain further information concerning liquid-film attachment, it is suggested that (at the present time) experimental studies might be most profitable.

As mentioned in section 1, it is possible that film cooling will be used for (among other things) the protection of the external surfaces of guided missiles and the internal surfaces of rocket-motor nozzles. If simple film-coolant injector holes are to be located on these surfaces, it would be necessary to study the film-attachment phenomena at supersonic gas velocities and for various surface geometries.

4 Stability of Liquid Films Flowing Under the Influence of Turbulent Gas Streams

A Previous Studies

The stability of thin liquid wall films flowing under the influence of high-velocity turbulent gas streams has been investigated experimentally by Kinney and Abramson of the National Advisory Committee for Aeronautics (8) and to a limited extent by Greenberg of Purdue University (7).

Kinney and Abramson observed visually annular liquid flow with concurrent turbulent air flow in horizontal transparent tubes. The surface of the liquid film was observed to be relatively smooth at low liquid-flow rates and disturbed markedly at higher liquid-flow rates. The authors reported that the liquid flow per circumferential length at which marked liquid-flow disturbances initially occurred increased with increased liquid viscosity, increased slightly with decreased liquid surface tension, and did not vary appreciably with changes of air-mass velocity.

Kinney and Abramson presented a portion of their data in the form shown in Fig. 5, where the heat-transfer results from a report by Kinney and Sloop (9) are included as well as the research results reported in Ref. 8. The curve is the dimensionless velocity correlation for adiabatic single-phase pipe flows which was given by Deissler (10); the abscissa is the dimensionless distance y^*, defined by $y^* = \rho_0\sqrt{\tau_0/\rho_0}(y/\mu_0)$, and the ordinate is the dimensionless velocity u^*, defined by $u^* = u/\sqrt{\tau_0/\rho_0}$, where τ is shearing stress, ρ is density, y is distance into the fluid stream measured perpendicularly to the duct wall, μ is dynamic viscosity, u is axial velocity, and the subscript 0 refers to the duct wall. The break in the curve of Fig. 5 indicates approximately the transition from the laminar region to the turbulent region. The points which have been singled out on the curve correspond to the values of the dimensionless film thicknesses at which the liquid-film

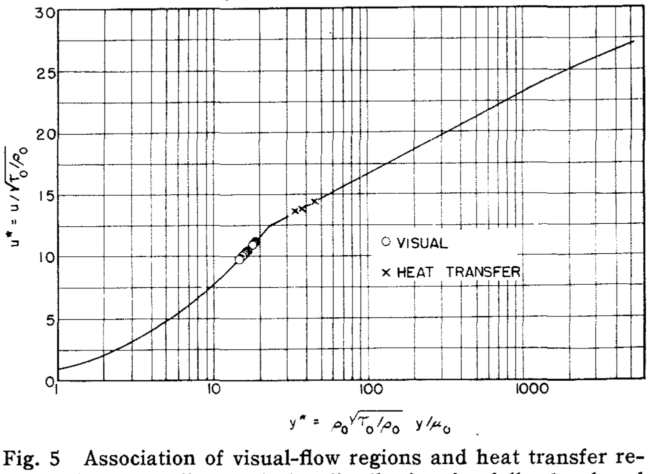

Fig. 5 Association of visual-flow regions and heat transfer results with generalized velocity distribution for fully developed flow in smooth tubes applied to liquid films (from Fig. 6 of Ref. 8)

surface initially became rough; they were singled out in order to indicate the magnitude of the critical dimensionless film thickness relative to the dimensionless laminar sublayer thickness for single-phase pipe flows. Kinney and Abramson subscribed to the hypothesis, suggested earlier by Colburn and Carpenter (11), that an annular liquid film flowing under the influence of a high-velocity turbulent gas stream behaves as the wall layer with the same thickness and shearing stress in single-phase liquid flow, and that it is essentially laminar when its thickness is less than the thickness of the laminar sublayer in the corresponding single-phase flow. Remarks on this hypothesis are included in section 4-C.

Of the quantitative results for flows in transparent tubes which were presented by Kinney and Abramson, it appears that those depending upon values of fluid properties which vary appreciably with temperature changes (especially those depending upon values of liquid viscosities) contain slight errors. The authors calculated fluid properties, assuming the film temperature to be the same as that of the entering fluids (i.e., 80 F); actually, the film temperature was more nearly the wet-bulb temperature corresponding to the relative humidity of the gas stream [see, e.g., Equation [39] of this paper]. Since the gas was virtually dry air (according to a personal communication from Kinney), this wet-bulb temperature was approximately 50 F, a temperature considerably lower than the 80 F of the entering fluids.

Greenberg, in his M.S. thesis, included nine photographs of annular liquid flow with concurrent air flow in a horizontal Lucite tube. In the first of these photographs (Fig. 23 of Ref. 7) the surface of the liquid film appeared to be relatively smooth. The other eight photographs, taken at higher liquid-flow rates, indicated varying degrees of liquid-film surface disturbance. No correlation of the inception points of the marked disturbances was attempted by Greenberg in the thesis.

B Experimental Results

During the present investigation, the dividing line between the areas of stable and unstable flow of annular liquid wall films in the presence of high velocity turbulent gas flow in a duct was detected indirectly, by inspection of mass-transfer data when heated gases were employed, and directly, by examination of the liquid film itself, when gases at room temperature were employed.

Data concerning the rate of mass transfer into a turbulent heated gas stream from a liquid wall film (averaged over the length of the film) were obtained for specified operating conditions by operating the test apparatus at the desired gas-flow rate, gas temperature, and liquid-flow rate until steady-state conditions were attained and then by recording (together with other pertinent data) the electric potentials created within thermocouples which were spot-welded to the exterior of the metal test duct. The axial position along the duct at which the wall temperature varied rapidly from a value below that of the boiling temperature of the liquid to a value approaching that of the hot gas stream was assumed to coincide with the axial position along the duct, corresponding to the end of the protective liquid film. Tests were conducted for gas-stream-diameter Reynolds numbers from 105,000 to 433,000, gas-stream temperature from 1103 to 2239 R, water-flow rates from 0.012 to 0.20 lb/sec/ft of tube circumference, and ambient pressures.

Results of the mass-transfer tests[7] were prepared for study by plotting water-flow rate vs. protected-surface area, test-section pressure drop vs. protected-surface area, and test-section pressure drop vs. liquid-flow rate. Curves with abruptly changing slopes were drawn through each set of points corresponding to a given set of gas-stream conditions.

For the direct study of the character of liquid wall films, a Lucite test section was installed in the test apparatus; study media included high-speed motion pictures, spark photographs, and visual observations aided by stroboscopic lighting.

High-speed motion pictures were taken for gas-stream-diameter Reynolds numbers from 239,000 to 664,000, water-flow rates from 0.031 to 0.12 lb/sec/ft of tube circumference, ambient pressures, and ambient temperatures. The pictures make manifest the following facts for the range of variables investigated: 1 Small disturbances with wave lengths of the order of 10 film thicknesses are present on the surface of the liquid film for all liquid-flow rates. 2 The scale of the small disturbances decreases as the diameter Reynolds number of the gas stream increases; the scale does not vary appreciably, however, when the liquid-flow rate is changed. 3 For liquid-flow rates larger than some critical value, long wave-length disturbances appear on the surface of the film. 4 The inception point of the long wave-length disturbances is independent of the gas-stream Reynolds number. 5 Liquid droplets are entrained by the gas stream from the crests (regions where relatively large quantities of liquid are collected) of the long wave-length disturbances.

Spark photographs were taken for gas-stream-diameter Reynolds numbers from 310,000 to 560,000, water-flow rates from 0.021 to 0.097 lb/sec/ft of tube circumference, ambient pressures, and ambient temperatures. Inspection of the original negatives confirmed items 1 through 4 of the preceding paragraph and presented additional detailed qualitative information concerning the structure of the disturbances. (These spark photographs, incidentally, do not reveal any film nonuniformities which may be attributed to the fact that the film was injected through discrete holes. This state of affairs is good; circumferential film nonuniformities are undesirable in most film-cooling applications.)

Visual observations aided by stroboscopic lighting were made for gas-stream-diameter Reynolds numbers from 307,000 to 595,000, test-section pressures from 14.1 to 28.9 psia, viscosity ratios (μ_{M_0}/μ_{Lf}) from 0.0052 to 0.0140 (obtained by using water and aqueous sucrose solutions), and ambient temperatures. For given gas-stream conditions and given fluid properties, the liquid-flow rate corresponding to the observed inception point of unstable liquid-film flow was determined in nine separate trials. The median of the flow rates corresponding to the nine trials was accepted for comparison with data obtained by other study mediums.

C Discussion of Data

Flows with Heated Gases: The abrupt changes in the slopes of the curves of protected-surface area vs. water-flow rate (one abrupt change for each curve) are interpreted to mean that two different types of flow are encountered in film-cooling applications. One type, found at relatively low liquid-flow rates, leads apparently to low mass-transfer rates, whereas the other type, found at relatively high liquid-flow rates, leads apparently to high mass-transfer rates. Obviously, the latter type of flow is to be avoided if efficient coolant usage is desired.

The fact that the curves of test-section pressure drop vs. liquid-flow rate (or vs. protected-surface area) possess abrupt changes in slope which are related to film-attachment efficiency and film stability can be accounted for if one examines the equations of steady one-dimensional gas flow as developed by Shapiro and Hawthorne (12). For further discussion of this topic, see Appendix A of Ref. 2.

Inspection of available data (including those presented by Kinney in Fig. 4 of Ref. 13) for the flow of heated air over a thin water film reveals that data corresponding to the inception point of unstable liquid-film flows (flows which are accompanied by high mass-transfer rates) may be presented in dimensionless form (6) by plotting the dimensionless film

[7] Data obtained during the film-stability and evaporation-rate studies described in this paper are presented in tabular form in Tables I through V of Ref. 2.

thickness corresponding to the inception point of unstable liquid-film flows as a function of the ratio of the gas-vapor-mixture viscosity to the liquid viscosity; the dimensionless film thickness is defined by $\eta^* = \rho_{Lf}\sqrt{\tau_0/\rho_{Lf}}\ (\eta/\mu_{Lf})$ and (assuming a linear velocity profile to exist in the liquid film) is calculated from $\eta^* = \sqrt{2\Gamma/\mu_{Lf}}$, where Γ is liquid flow per unit time and per unit length of tube circumference, η is average film thickness, the subscript Lf refers to the liquid in the film, and the viscosities are evaluated at the liquid-film surface temperature. The film temperatures were calculated using Equation [39], and the mixture viscosities were calculated using the procedure suggested by Bromley and Wilke (14).

Since the liquid viscosity appears in both the abscissa and the ordinate of Fig. 6 and the gas-vapor-mixture viscosity did not vary appreciably for the tests, it is interesting to replot the data after dividing the ordinate by the viscosity ratio (Fig. 7). Further comments on Figs. 6 and 7 are withheld until later in the discussion.

Flows with Unheated Gases: Data for gas flows at ambient temperatures have been added to Figs. 6 and 7; the film temperature was assumed to be equal to the wet-bulb temperature in the case of a water film and to the temperature (measured) of the exhausted liquid in the case of a film of aqueous sucrose solution.

The data presented in Figs. 6 and 7 are for gas-stream-diameter Reynolds numbers from 105,000 to 2,900,000; duct diameters from 2 to 4 in.; test-section pressures from 14.1 to 28.9 psia; temperature ratios T_∞/T_0 from 1.0 to 3.5; and mass-flow ratios $\dot{m}_0/\rho_\infty u_\infty$ from zero to 0.0015 (where T is temperature, and m is mass transfer per unit area and per unit time). Since the viscosity ratio μ_{M_0}/μ_{Lf} (where subscript M refers to the mixture of gases) did not vary monotonically with any of these parameters, the curves presented may be taken to be general curves which are valid for liquid-gas combinations other than those investigated (provided, of course, that the several parameter values do not vary too greatly from the ranges investigated).

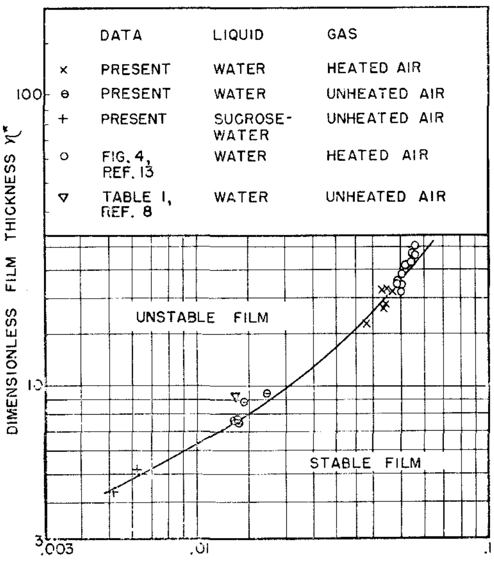

Fig. 6 Dimensionless film thickness vs. ratio of viscosity of gas vapor mixture to that of liquid at inception point of long wave-length disturbances

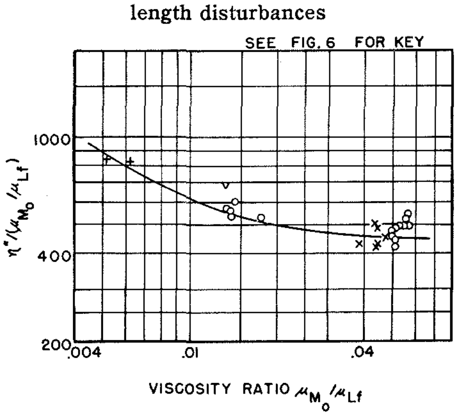

Fig. 7 Dimensionless film thickness η^* divided by μ_{M_0}/μ_{Lf} ($= \rho_{Lf}\sqrt{\tau_0/\rho_{Lf}}\,\eta/\mu_{M_0}$) vs. μ_{M_0}/μ_{Lf} at inception point of long wave-length disturbances

The hypothesis that an annular liquid film flowing under the influence of a high-velocity gas stream behaves as a part of a single-phase boundary layer is now seen to be incorrect. Whereas the laminar sublayer thickness in a single-phase boundary layer is defined completely by the dimensionless thickness y^*, Fig. 6 indicates that the maximum allowable thickness of a stable liquid wall film flowing under the influence of a high-velocity gas stream depends upon both the dimensionless thickness η^* and the viscosity ratio μ_{M_0}/μ_{Lf}. The basis for this observed dissimilarity has not been established; it is suspected, however, that the velocity profile as influenced by the viscosity discontinuity at the liquid-gas interface has an appreciable effect on the stability of the liquid wall film (see Fig. 8 for a sketch of a velocity profile typical of that encountered in the case of a stable liquid wall film flowing under the influence of a turbulent gas stream).

Although dimensionless parameters (e.g., the ratio η/δ) other than those used in Figs. 6 and 7 have been examined, only those used in Figs. 6 and 7 were found to be satisfactory for data presentation.

Summarizing, examinations of data concerning mass transfer from liquid wall films, inspections of high-speed motion pictures and spark photographs of liquid wall films, and visual observations of liquid wall films led to the conclusion that the presence of unstable long wave-length disturbances on a liquid-film surface was accompanied by relatively high mass-transfer rates (due, at least in part, to the loss of liquid droplets from the unstable film surface to the gas stream); hence, the unstable long wave-length disturbances are to be avoided when designing for an efficient film-cooling system. All available data corresponding to the inception point of instability for liquid wall films flowing under the influence of high-velocity gas streams are presented in dimensionless form by plotting the dimensionless film thickness corresponding to the inception point of stability as a function of the ratio of the gas-vapor-mixture viscosity to the liquid viscosity, where the viscosities were evaluated at the liquid-film surface temperature.

The dimensionless parameters which were used in the presentation of the data obtained at the inception point of film instability (Figs. 6 and 7) are speculative inasmuch as the liquid density ρ_{Lf} and gas viscosity μ_{M_0} were not varied appreciably during the tests. Experiments with various liquid densities and various gas viscosities are required for the com-

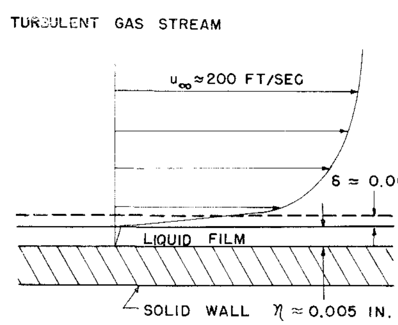

Fig. 8 Velocity diagram for typical stable liquid wall film flowing under influence of turbulent gas stream (liquid-film surface velocity $u_0 \approx 3$ ft/sec, characteristic length of small disturbances ≈ 0.1 in.)

plete confirmation of the dimensionless parameters used in Figs. 6 and 7.

Since the small disturbances which have been observed on the surface of a liquid film flowing under the influence of a turbulent gas stream appear to be related to the gas-stream turbulence, a complete analytical investigation of their origin would be difficult. However, much useful information could perhaps be obtained from an analysis of the stability of Couette flow with two layers of fluid of different densities and viscosities. Such a flow might be stable to small oscillations for all Reynolds numbers, but it is possible that the wave lengths and velocities of the least-damped oscillations are related closely to the small disturbances observed on the surface of a liquid film. The fact that the wave length of the small surface disturbances has been observed to be approximately 10 film thicknesses makes the suggested analysis appear promising; a typical result of stability analyses is that the least-damped oscillations have a wave length of the order of ten times the characteristic length of the flow field.

The Mechanics of Film Cooling—Part 2

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5 Evaporation From Stable Liquid Wall Films into Heated Turbulent Gas Streams

A Previous Studies

Of the several works published in recent years on evaporation from annular liquid wall films into heated turbulent gas streams, only the most comprehensive papers are reviewed here. These are the theoretical paper by L. Crocco (15) and the experimental paper by Kinney (13); both papers appeared in 1952.

Crocco extended Rannie's (16) approximate theory of porous-wall cooling for inert coolants to porous,[8] sweat, and film cooling for the case in which the coolant itself is reactive with the hot gas stream. The liquid film was assumed to be stable, and axial gradients were neglected in comparison with radial gradients. Crocco divided the gas stream into two regions: a central turbulent core where the gases are not affected by the addition of mass at the boundary, and a laminar sublayer adjacent to the boundary where all the effects of mass addition are confined. (The boundary referred to may be either a liquid-gas interface or a porous wall, the choice depending upon the type of cooling which is employed.) In the turbulent core, the Reynolds analogy was extended to read

$$\frac{\theta_\infty - \theta_\delta}{\dot{w}_\delta} = \frac{H_{t\infty} - H_{t\delta}}{\dot{q}_\delta} = \frac{u_\infty - u_\delta}{\tau_\delta} \qquad [1]$$

where θ is the oxidizer specific concentration (weight of oxidizer per unit total weight), $\dot{w}$ is oxidizer transfer per unit area and per unit time, H is enthalpy, $\dot{q}$ is heat transfer per unit area and per unit time, the subscript ∞ refers to bulk properties or average velocity, the subscript δ refers to the junction of the laminar sublayer and the turbulent core, and the subscript t refers to total (indicating that chemical energy, but not kinetic energy, of the fluid should be included). The thickness

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[8] Crocco defined porous cooling as "cooling through a porous wall with a gas or a liquid vaporized before entering the wall" and sweat cooling as "cooling through a porous wall where the coolant is liquid throughout the wall."