THE UNIVERSITY OF MICHIGAN

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Report No. UMICH 012449-23-I

LIQUID FILM THICKNESS MEASUREMENTS IN UNIVERSITY OF MICHIGAN WET STEAM TUNNEL

1976 ASME Cavitation Forum (#3)

by

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Financial Support Provided by:

National Science Foundation
Grant No. 40130

December 1975

I. INTRODUCTION

The initial results from the wet-steam flow research program at the University of Michigan have been described previously in this very Forum in 1974. This program is concerned with both the behavior and stability of thin liquid films upon simulated turbine blades under high velocity steam flow, and with their subsequent breakup into liquid droplets, which are then entrained into the wake, giving rise to an erosion problem in the next downstream rotating row. The problem of thin liquid film behavior in the non-adiabatic case has application also to problems of "dry-out" in high void fraction boiling, particularly with regard to emergency core cooling of liquid-cooled nuclear reactors.

For this research program we have designed and constructed a low-pressure wet steam tunnel producing an approximately sonic velocity ($\sim$450 m/s) in a rectangular test section (8 cm x 8 cm) at a pressure of $\sim$ 3 psia. Simulated turbine blades, i.e., essentially thin flat plates, are inserted parallel to the flow direction along the axis of the test section. In the case of the particular profile, with which the tests herein discussed were performed, 4 electrical conductivity liquid film gages were installed along the axis, evenly spaced. A liquid film was injected 3/4" upstream from the first gage. The behavior of this film under adiabatic conditions is the primary subject of this paper. The development and calibration of the gages as well as fuller details on the results here discussed are reported elsewhere (2-4).

II. EXPERIMENTAL FACILITY AND APPARATUS

Steam conditions in the test section are near saturation (never superheated), showing varying degrees of moisture depending primarily upon test section velocity (Table 1). Of course, wetness increases with velocity head for fixed supply conditions. Supply conditions are essentially constant.

Table 1

V_{steam} (ft/sec.)	T (^oF)	P ($lb/in.^2$)	X (Quality)
200	130	2.2	0.99
600	130	2.2	0.98
1500	130	2.2	0.95

A. Blading Profiles

A symmetrical thin blading profile (Fig. 2) has been fabricated.

It can be used either with internal water cooling to induce condensation or, as was in fact done for these tests, with a water film injected through a small slit normal to the tunnel axis.

Good still photographs of both the condensed and injected liquid films were presented previously (1, 3,eg). Typical photos are repeated here for convenience (Fig. 1). Since obtaining these photos, electrical conductivity film thickness gages have been installed and calibrated statically (2,3). The primary subject of the present paper is the test results after installation of the film thickness gages.

B. Electrical-Conductivity Thickness Gages (2,3)

The electrical resistance* of a thin liquid film connecting the central pole of the gages with an external annulus (separated by an electrical insulator), all installed flush with the blade surface (Fig. 2), is measured by an a.c. circuit including a Wheatstone bridge. Response time is very fast so that the frequency and amplitude of local film surface waves as well as "mean thicknesses" can be measured. An a.c. circuit is necessary to avoid problems of electrostatic charge. Response is relatively flat with frequency in the range of 1 kHz, which is thus utilized. A schematic of the gage design is shown in Fig. 3. Gage

*An aqueous solution with 0.5% NaCl (by mass) is used.

output (in terms of circuit conductivity) is approximately linear for small film thicknesses, and they essentially saturate at higher thicknesses (Fig. 4). Thus the useful operating range of the gages is limited, but sufficient to provide considerable useful data, as here reported.

III. EXPERIMENTS PERFORMED

Since the injected water film temperature is about equal to that of the steam ($\sim 120^{o}F$), the tests are essentially adiabatic. The maximum steam velocity is about sonic ($\sim$ 450 m/s or $\sim$ 1400 f/s). No limiting minimum velocity exists other than that imposed by measuring precisely. The minimum velocity we have used is $\sim$100 f/s. Very low velocities are desirable for the investigation of liquid film stability, which is not within the scope of this paper (see ref.3,4).

The liquid film is injected through a narrow slot across the blade (Fig. 2) near its leading edge. Minimum practical injection rate is $\sim$ 5 cc/m. Maximum injection was limited by the onset of spraying and jetting to $\sim$ 60 cc/m.

Visually (by strobe light or photographically as Fig. 1) and also from the output of the thickness gages (4, eg), the film thickness is in general not uniform in time or space, and in fact often includes an apparently complex wave pattern. Also at some times "dry spots" and/or an axial filament flow pattern have been observed. The photos of Fig. 1 ($\sim$1 μs exposure) are typical for both film and wake. Droplets of 0.05-0.1 mm dia. have been observed. Apparent back-flow on the trailing tapered portion of the blade has also been observed (Fig. 1), perhaps induced by the slight adverse pressure gradient due to increased flow area from blade.

The film thickness gages (Fig.2,3) produce instantaneous film thickness measurements at four evenly spaced locations along the axis of the upper blade surface. Hence time average as well as time dependent thicknesses are provided.

The existence of 4 gages spaced axially allows also a measurement of film thickness variation along the blade, discussed elsewhere (3 and 4).

The time average values can be directly related to axial shear between steam and liquid, assuming the liquid film flow to be laminar ($Re_{max} \sim 40$, and liquid velocity $\cong 0.1$ f/s). Thus a classical uniform shear (Couette) flow with film velocity varying linearly with distance from blade surface is produced. The steam flow is of course turbulent so that shear from the steam side can only be estimated from friction factor data, since steam axial pressure drop is too small for accurate measurement.

IV. RESULTS - EXPERIMENTAL AND THEORETICAL

The steady-state flow regime can be analyzed assuming equality of axial shear between steam and liquid at the interface. Since there is no steam acceleration pressure drop, the entire drop is frictional. Since it is too small to be measured accurately, it can only be estimated through fluid friction pressure drop calculations; using the concepts of hydraulic diameter and friction factor, where f = f (Re). Since experimental data is limited to flow with solid walls with known roughness, the friction factor between liquid and gas is not well known.

Interface shear can be related to the thin liquid film flow regime assuming it to be a constant shear Couette flow with linear velocity profile

$$V_{liq_{max}} = \tau (h/\mu_{liq}) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

The continuity equation can also be applied for the liquid flow to give a relation between the injected flow rate, $\dot{m}$, the film thickness, h, and the maximum liquid axial velocity (at the steam-liquid interface), assuming adiabatic flow with no evaporation or condensation, i.e.,

$$\dot{m}_{liq} = \rho \bar{V}_{liq} A_{liq} = \rho (\bar{V}_{liq_{max}}/2) bh \quad \ldots\ldots \quad (2)$$

where b is blade width.

Combining Eqs. (1) and (2), interface shear, τ, can be related to h for curves of constant $\dot{m}$. τ can also be computed for fixed test section steam conditions as a function of steam velocity, V_{steam}. It is then obviously possible to relate film thickness, h to test-section steam velocity, V_{steam} with $\dot{m}$ as curve parameter, thus obtaining a theoretical prediction for film thickness for fixed flow test parameters. These can then be checked against measured film thicknesses (Fig. 5).

Figure 5 summarizes the theoretical expectations concerning film thickness as a function of steam velocity for different injected liquid film flow rates. Two major trends are shown, i.e., film thickness, h, decreases for increasing steam velocity (more strongly at small steam velocity), and it increases for increasing injected film flow rate. The anticipated effect with increasing film injection rate is intuitively obvious, and that with steam velocity can be explained on the basis that increasing V_{steam} means increased liquid velocity, and reduced film thickness. Figure 5 also includes a curve for $h_{crit.}$, the critical film thickness, where according to a recent analysis (based on the conservation of kinetic and surface energy) it could desintegrate into individual axial liquid filaments (5).

Figure 6 compares measured film thicknesses with those theoretically predicted for an intermediate film injection flow rate. These results are typical and full data is given elsewhere (3). No differentiation between points for different axial positions is made here. The experimental data confirm the two major trends predicted theoretically, i.e., increasing film thickness for increasing film injection rate and decreasing steam velocity. While there is much experimental scatter and also high frequency oscillation of the gage output, the "best curves" show film thicknesses about twice those expected theoretically. The "error" in film thickness is only a few mils, and there are many possible considerable sources of error in the reduction of both theoretical and experimental data. Thus the degree of agreement rather than the discrepancy may be the more remarkable. However, we have no specific explanation for the systematic discrepancy found (Fig. 6). An inaccurate estimation of the friction factor, f, could be partly responsible. Then, f would need to be reduced two-fold. This seems unlikely to be realistic, since "hydraulically smooth" walls were assumed. However, to our knowledge, no actual friction measurements for interfacial fluid friction pertinent to the present case exist. Of course, the observed surface waves could increase the friction substantially.

Surface wave frequencies have been estimated from scope pictures of thickness gage output (5). Typically ~ 10 kHz was noted.

V. CONCLUSIONS

1) Measured (average) liquid film thicknesses agree qualitatively very well in that the film thickness decreases with steam velocity and reduced injected film flow rate roughly in the proportions predicted. Thicknesses were computed assuming the liquid film to be laminar, uniform and steady-state. The laminar assumption appears well justified, but film appears neither uniform nor steady-state, rather exhibiting numerous (~ 10 Hz) surface waves.

2) Quantitative agreement is relatively poor in that the predicted thicknesses are ~ 1/2 those actually measured. The uncertainty of friction factor between steam and liquid surface is a partial explanation. However, friction factors ~ 1/2 those for hydraulically smooth pipe would be necessary to achieve agreement, and this does not seem probable.

VI. REFERENCES

1. F. G. Hammitt, A. Keller, G. Ernst, "Low Pressure Wet Steam Tunnel - Initial Results," ASME 1974 Polyphase Flow Forum, 13-15.

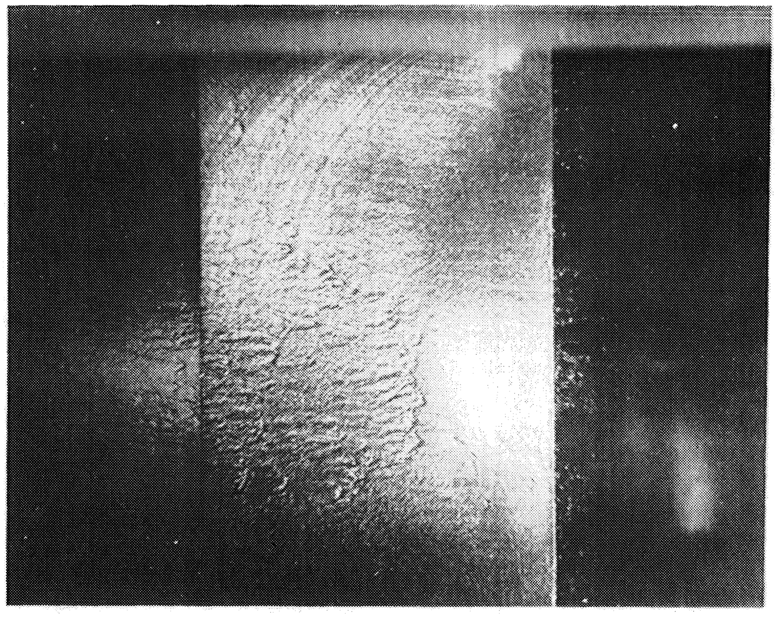
2. J. Mikielewicz and F. G. Hammitt, "Generalized Characteristics of Electrical Conductance Film Thickness Gauges," ORA Rept. UMICH 01244-7-I, Dec. 1974, U. of Mich., Ann Arbor, see also Trans. Inst. Fluid Flow Mach., Polish Acad. Sci., 1975.

3. F. G. Hammitt, J. Mikielewicz, G. Ernst, D. Krause, L. Rockwell, "Steam Tunnel Program and Liquid Film Thickness Gauge Developments at University of Michigan," ORA Rept. No. UMICH 012449-6-T, Jan. 1975.

4. F. G. Hammitt, J. B. Hwang, et al, "Liquid Film Tests, Wet Steam Tunnel", ORA Rept. UMICH 012449-9-T, Univ. of Mich, Ann Arbor, Mich, Dec. 1975.

5. J. Mikielewicz, J. R. Moszynski, "Breakdown of a Shear Driven Liquid Film," Proc. Inst. of Fluid Flow Machinery, Polish Acad. Sci., Gdansk, Poland, 1975.

VII. LIST OF FIGURES



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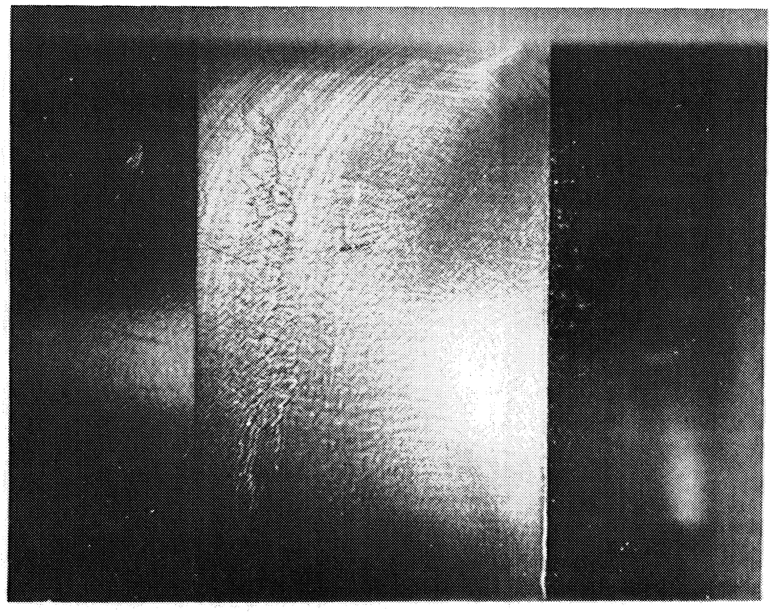
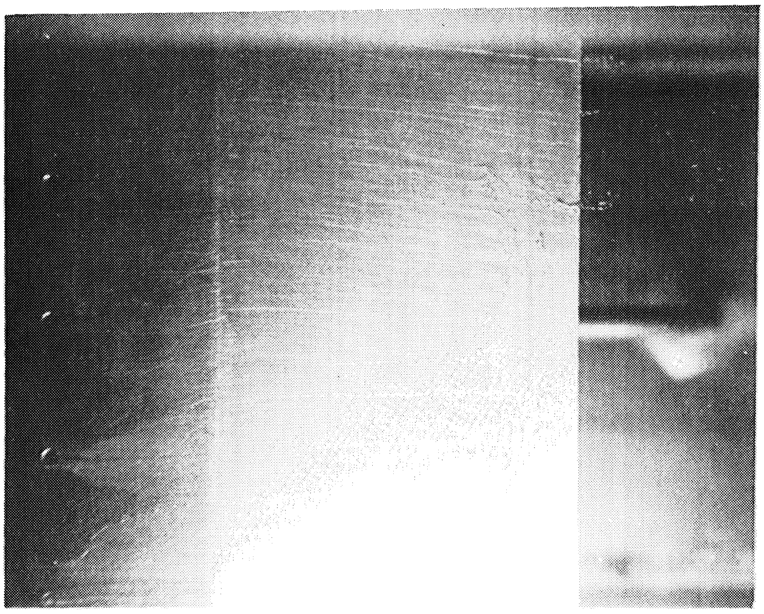
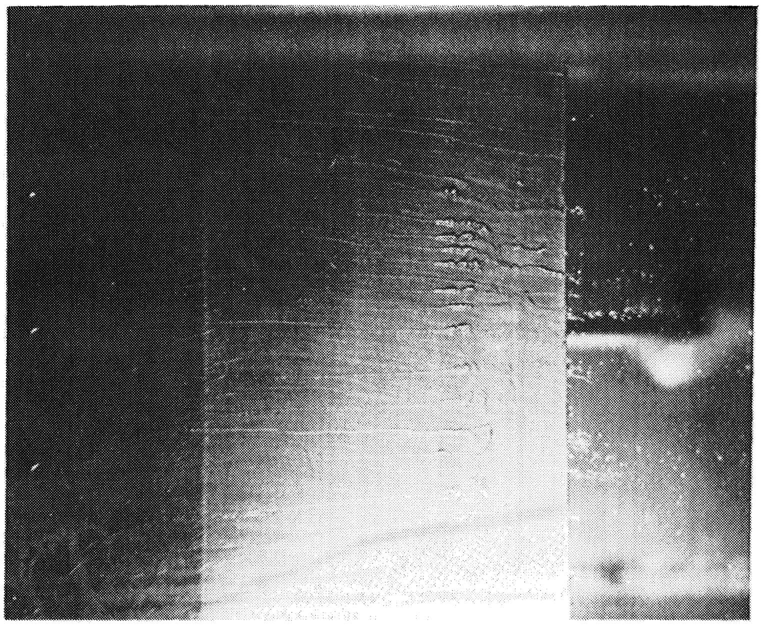


10 cc/min.

Fig. 1-a. Film and Droplet Photos - Injected Water Films



Cooled Blade, Condensed Water Film. Steam Velocity = 415 m/s,



Cooled Blade, Condensed Water Film, Steam Velocity = 415 m/s,

Fig. 1-b. Film and Droplet Photos - Condensed Films

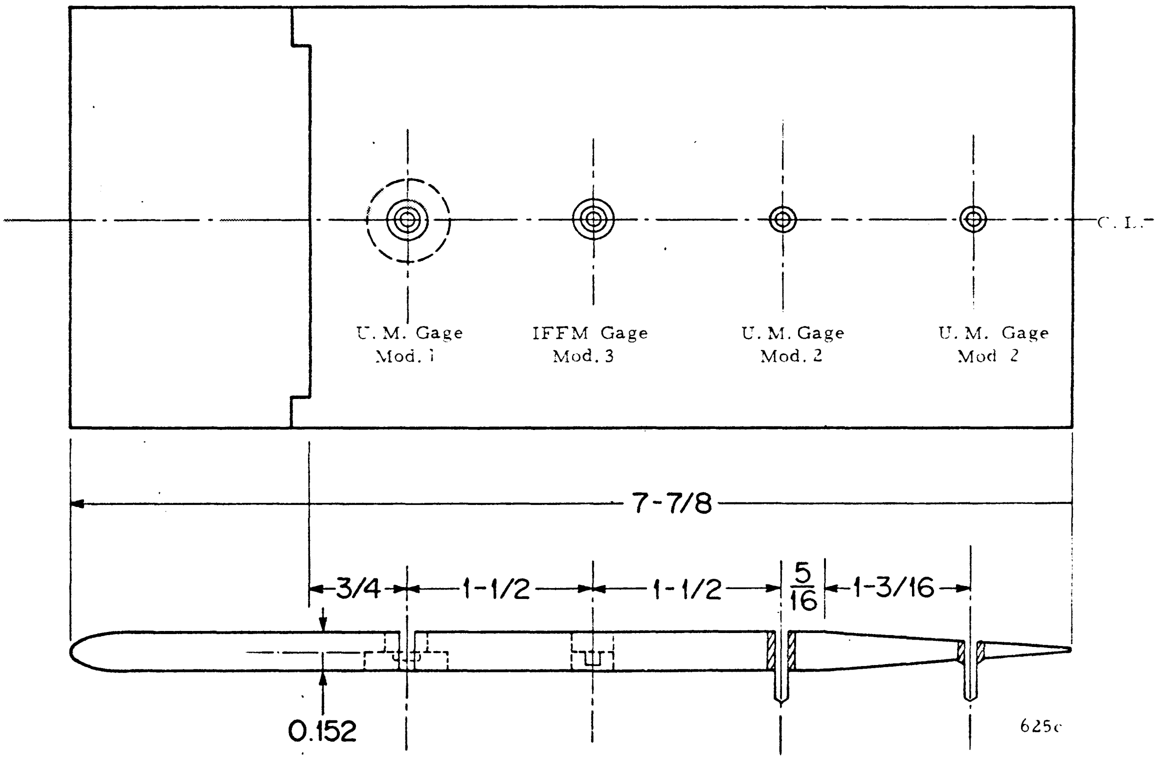


Fig. 2. Schematic of Blade with Gages

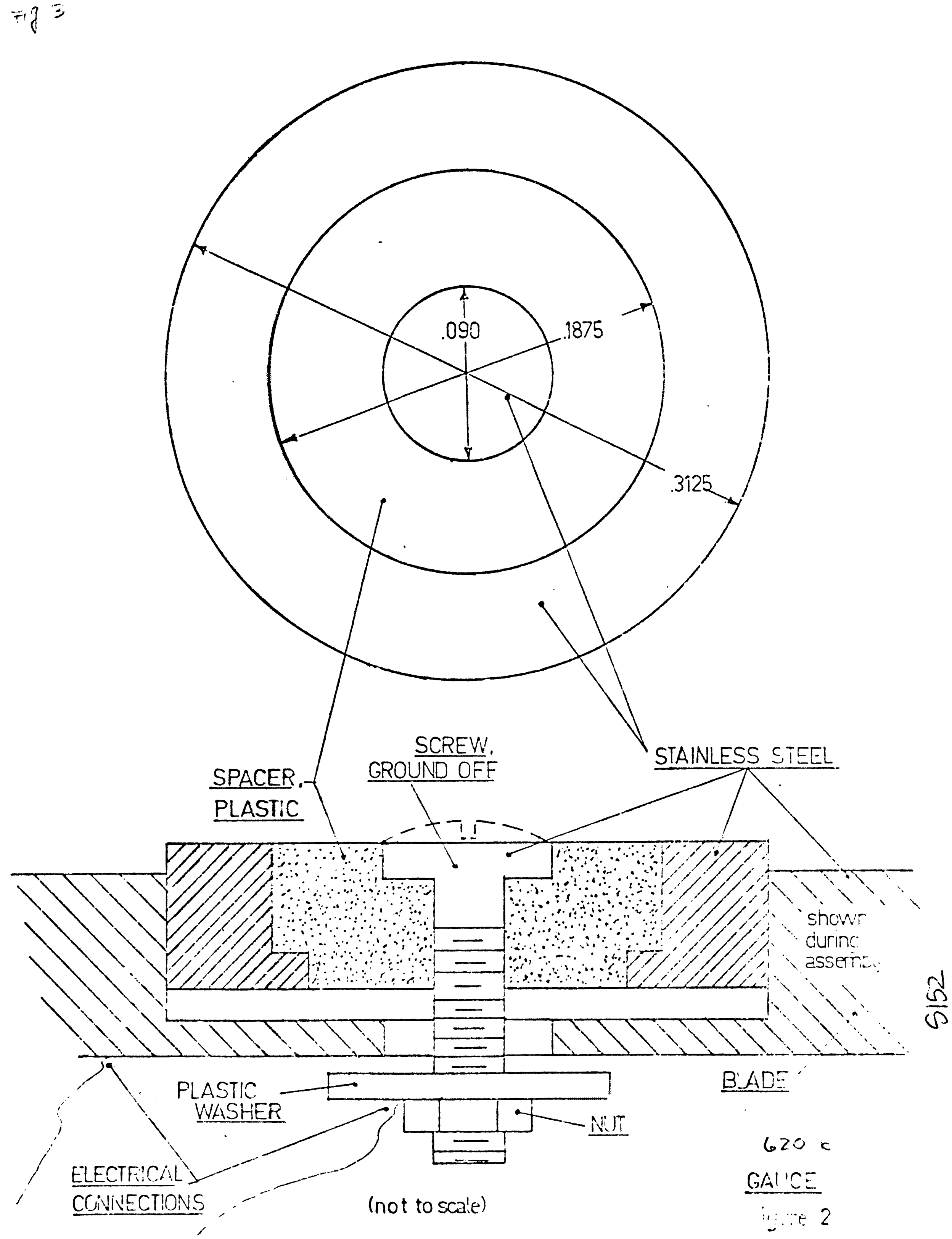


Fig. 3. Electrical Conductivity Gages

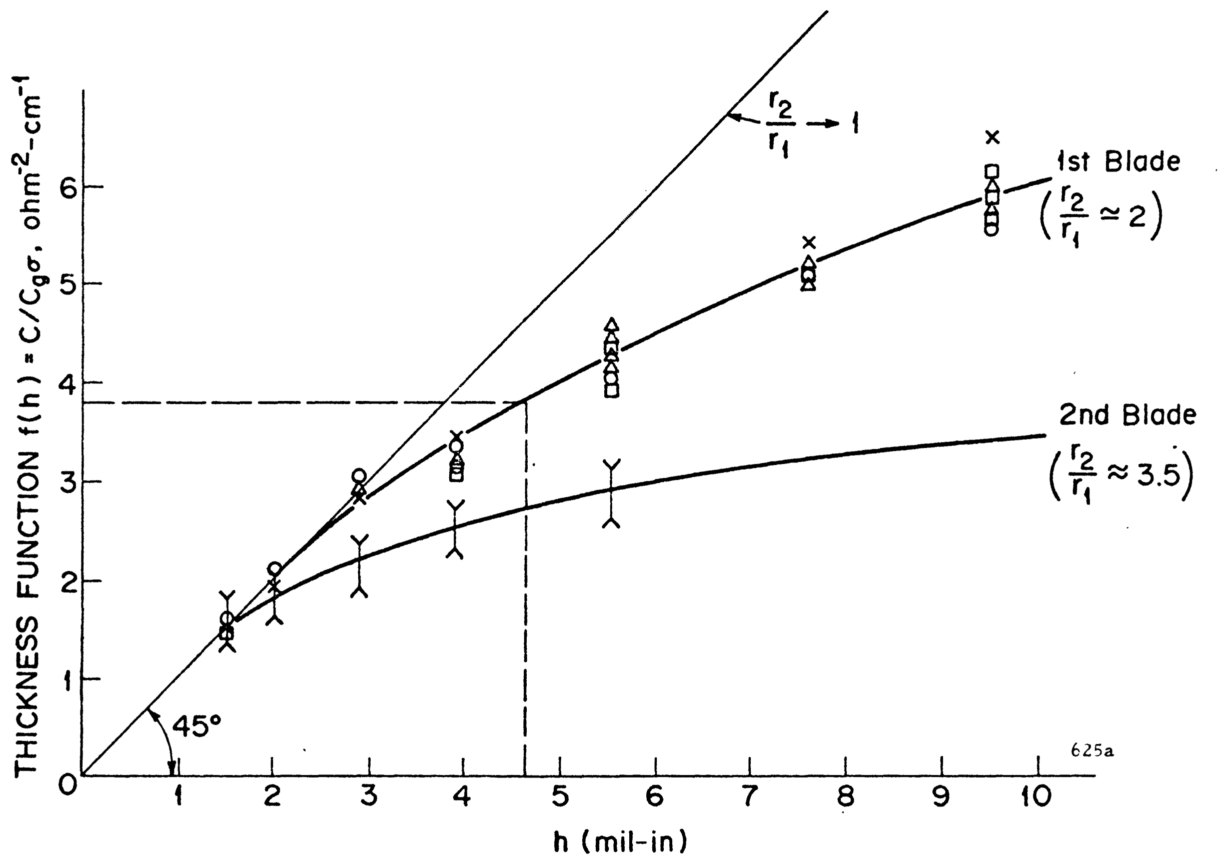


Fig. 4. Generalized Characteristics for Gages Investigated

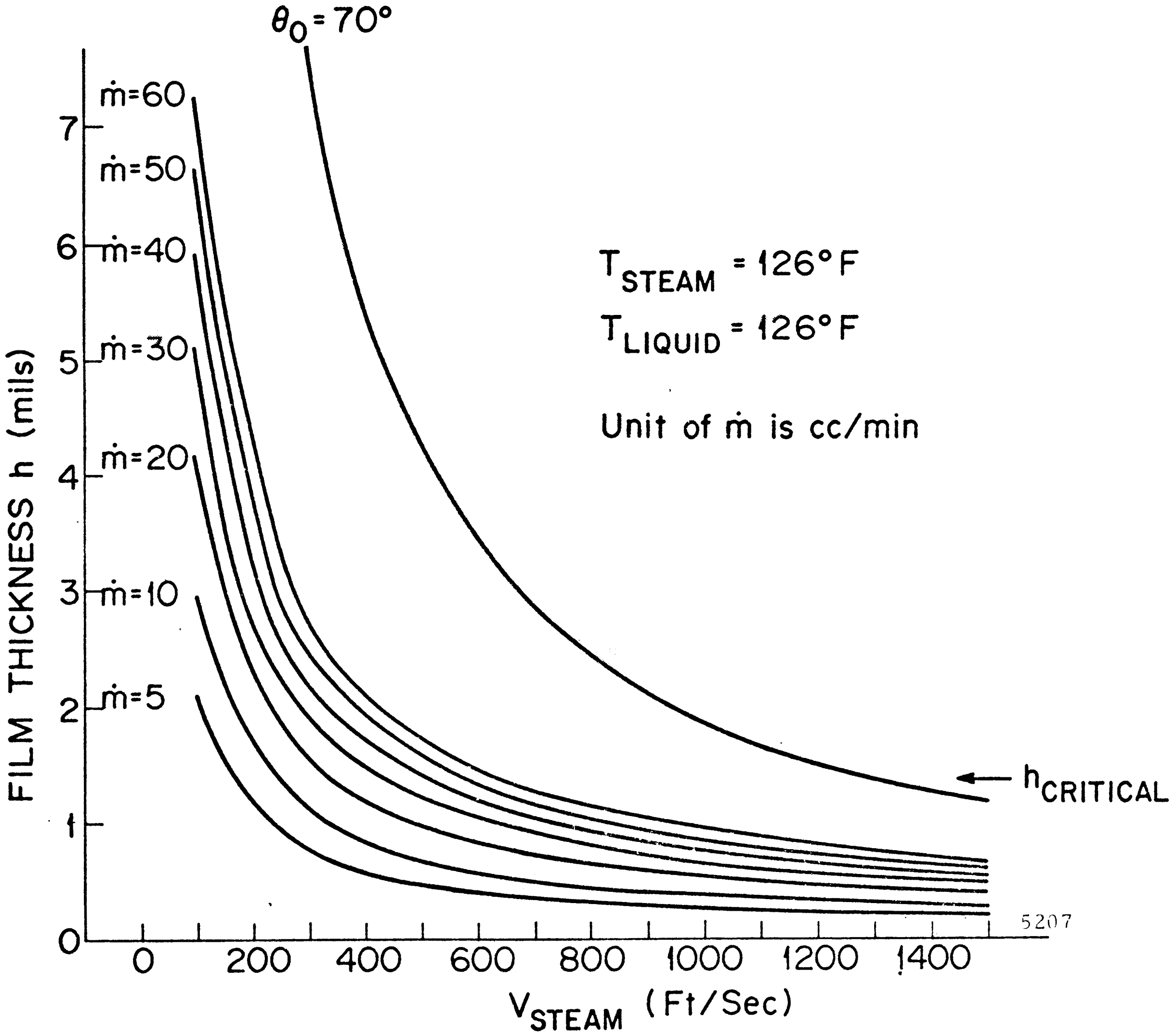


Fig. 5. Predicted Adiabatic Film Thickness vs. Steam Velocity; Various Film Flow Rate = 30 cm^3/min.

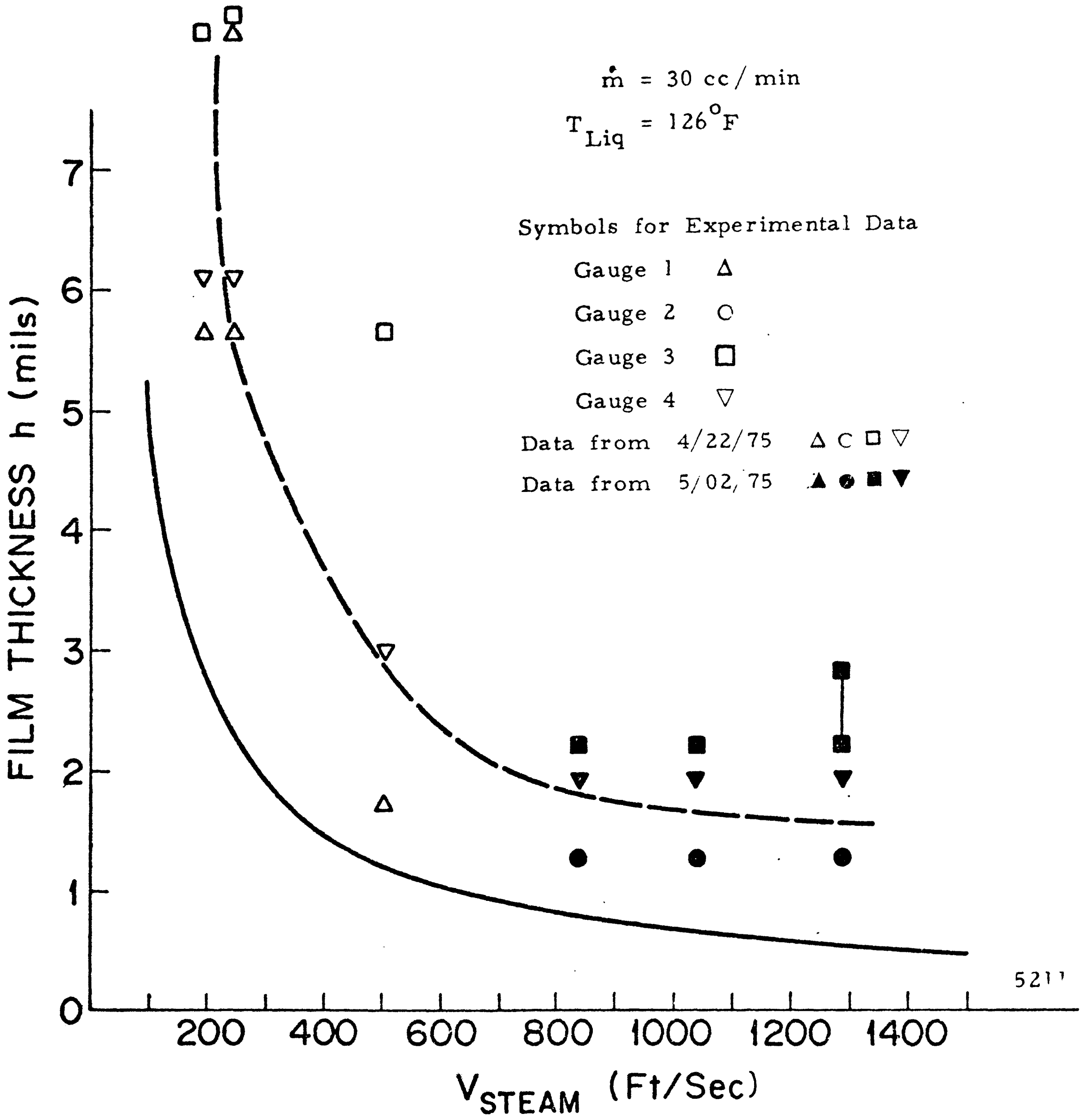


Fig. 6. Experimental Adiabatic Film thickness vs. Steam Velocity; Liquid Film Flow Rate = 30 cm^3/min.