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Department of Mechanical Engineering
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~~(Model 1)~~

"Thin Shear Driven Water Film Wavelet Characteristics"

(Submitted to 1977 ASME Cavitation and Polyphase Flow Forum)

by

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INTRODUCTION

Preliminary results from the wet-steam flow research program at the University of Michigan have been described at this Forum in 1974 and 1975. In brief, the research involves the behavior and stability of thin-liquid films upon simulated turbine blades under high velocity, low-pressure wet steam conditions, up to Mach 1, and its subsequent break-up into water droplets, which are then entrained into the wake creating an erosion problem in the next rotating row. The structure of water droplets in the steam flow was studied, and the Mach and Weber number dependence of drop size distribution was described. (1)

Recently, we have studied film surface wavelet patterns and measured wave length, and film thickness under various flow conditions (3,4). We found that wave lengths decrease as either water flow rate or steam velocity is increased. Also a 'transition map' was presented for different wave regimes as a function of water flow rate and steam velocity (3,4). However, only a very qualitative description of wave characteristics was given.

We have now obtained more precise film thickness and frequency data, which along with some quantitative analysis is here presented. The effect of the film waviness upon the shear-driven film flow is considered and experimental data have been compared with theoretical models. The first model assumes a smooth wall and the second is with equivalent sand roughness, so that $\epsilon_s = 2h$.

EXPERIMENTAL FACILITY AND APPARATUS

Figure 1 is a schematic of our steam tunnel facility. Figure 2 shows blade details in the test section. Electrical conductivity gages for film thickness measurement were developed and calibrated (1). Film thickness and wave frequency were thus measured.

Liquid film behavior and stability were studied by high-speed still camera, using $\sim 1\ \mu s$ flash. Different wave patterns and wave length measurements were made from the photos (Figs. 3,4).

EXPERIMENTAL AND THEORETICAL RESULTS

A. Wave Celerity for the Water Film Surface

Figure 5 shows that the ratios of wave celerity to mean film velocity (C/V_f) fall in the range $\sim 0.4 - 5.6$ as a function of film Reynolds Number (Re_f) and steam Reynolds Number (Re_s). At a smaller Re_s ($\sim 2.2 \times 10^6$), the ratio (C/V_f) increases as Re_f increases, but at a higher Re_s ($\sim 9.0 \times 10^6$), C/V_f decreases as Re_f increases. In general, all the data points fall in the region above the line, $\log_{10}(\frac{C}{V_f}) = 1.35\ Re_f - 0.7$.

Levich (5) has shown, starting from the Kapitsa (6) equation (modifed Navier-Stokes equation with gravity driven liquid film flow), the wave celerity should be 2.4 times the mean film velocity, while Benjamin (7) and Hanratty and Hershman (8) predicted $\frac{C}{V_f} = 3$. However, their experimental geometry is different from ours. (Vertical gravity-driven film flow).

Also Taylor et al (9) have reported on wave velocities in upward concurrent gas-film flow. It was found that the wave velocity increased rapidly with increasing gas flow rate, but varied little with liquid flow rate. It was found, furthermore, that the individual wave velocities were not uniformly distributed around the mean value under given flow conditions, but certain preferred velocities appeared to exist. The reasons for this behavior are not clear at present. Further, these effects in general were not reflected by our data.

Figure 6 shows the dependence of a wave Reynolds number , Re_w (= $\frac{4\,C\,h}{\nu}$), on Re_s and Re_f. It is apparent that Re_w increases as film Reynolds number increases. Also as Re_s is increased, Re_w has linear relation with Re_f on a semi-logarithmic plot, but at low Re_s, the Re_w is quite scattered from the linear relation. The observed celerity for small wavelets is $\sim$ 10 times the prediction based on shallow gravity wave assumptions, i.e., "hydraulic jump". However, the celerity for larger waves is much greater than computed on a basis of either gravity waves or surface-tension ("capillary") waves. Full tabulated values are found in ref. 12, omitted here for brevity.

B. Effect of Film Waviness on Film Flow

As described in our 1976 Forum paper and also elswhere (13), the steady-state flow film regime can be analyzed assuming equality of axial shear between steam and liquid at the interface, and laminar film flow. Sample calculations indicate that the film Reynolds number is $\sim$10 — 100 so that this assumption is well justified. Since no steam acceleration is involved, the entire pressure drop is due eventually to wall friction. We estimated this frictional pressure drop using the concepts of hydraulic diameter and friction factor, f = f (Re, $\frac{\epsilon_s}{d}$). At that time (13) we assumed f to be for a "smooth" wall. However, our photographs (Figs. 3, 4) indicate substantial film waviness which no doubt contributes to the effective surface roughness.

Hanratty (10) and Kordyban (11) have reported that the ratio of equivalent sand roughness to the root-mean-square of the fluctuations in the height of the liquid film is approximately equal to $3\sqrt{2}$. However, their experiment differed from ours in that relatively low velocity air-water channels were used. Since our wave troughs (thickness gage data) penetrate almost to the blade surface, the double mean film thickness can be approximately taken as a measure of the geometric roughness. (i.e., $\epsilon_s = 2\ h$). Theoretical film thickness, h is then given by the functional relation

$$h = F\ (Q,\ V_s,\ f)$$

where

h = average film thickness

Q = water film flow rate

V_s = steam velocity

$f = f\ (Re_s,\ \frac{\epsilon_s}{d} = \frac{2\ h}{D_{hyd}})$ = friction factor

Thus film thickness, h is a function of h itself. A trial and error method was then used to get the theoretical film thickness h in the new model. The experimental film thickness results are compared with theoretical predictions for smooth and rough wall models in Fig. 7. Good agreement is achieved.

Full tabulated data are not included in this paper in the interests of brevity. However they can be found in our project reports (12-14).

CONCLUSION

A. The ratio of surface wave celerity to average film velocity as a function of steam Reynolds number and film Reynolds number are presented and compared with other theoretical predictions, (i.e. Kapitsa, Benjamin and Hanratty). Small wave celerity is found to be $\sim$10 times the shallow gravity wave, but large wave celerity is much geater than predicted either by gravity or capillary wave theory.

Present data are quite scattered, but fall within the range above the empirical relation $\frac{C}{V_f} = 10^{(a\,Re_f - b)}$ line, where a = 1.35 and b = 0.7

B. Wave Reynolds number $(\frac{4\,C\,h}{\nu})$ increases with increased film Reynolds number. As the steam Reynold Number (Re_s) increases, experimental results approach a functional relation of the type, $\log Re_w = C\,Re_f + D$.

C. Influences of water film waviness upon the concurrent steam flow were considered, and experimental results were compared with theoretical predictions based upon: (a) smooth wall and (b) equivalent wave sand roughness. The required equivalent sand roughness of wavy film, to obtain a match with the present data turns out to be more than 2 h , where h is average film thickness.

ACKNOWLEDGMENTS

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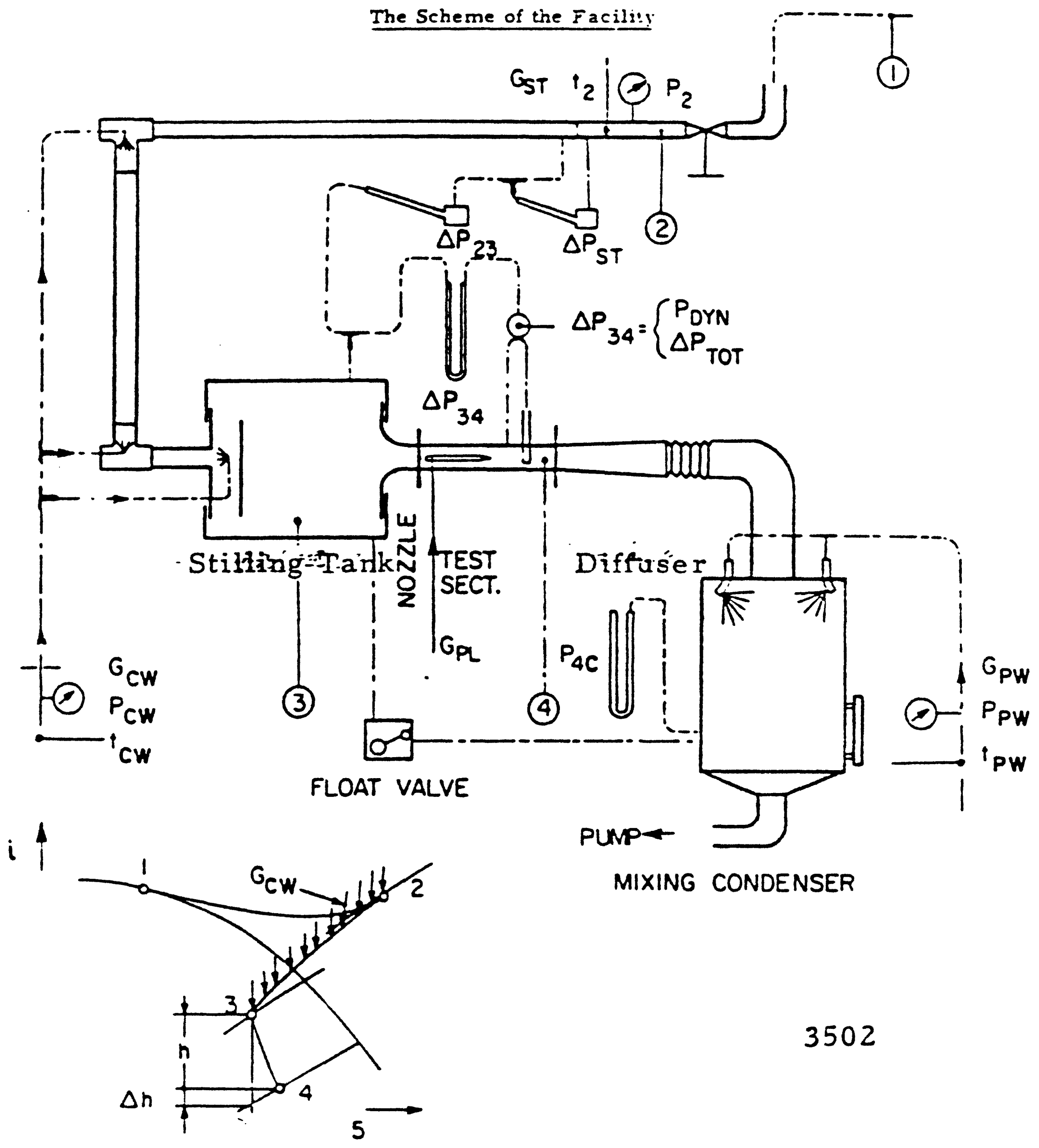

Fig. 1 Schematic of Steam Tunnel Facility

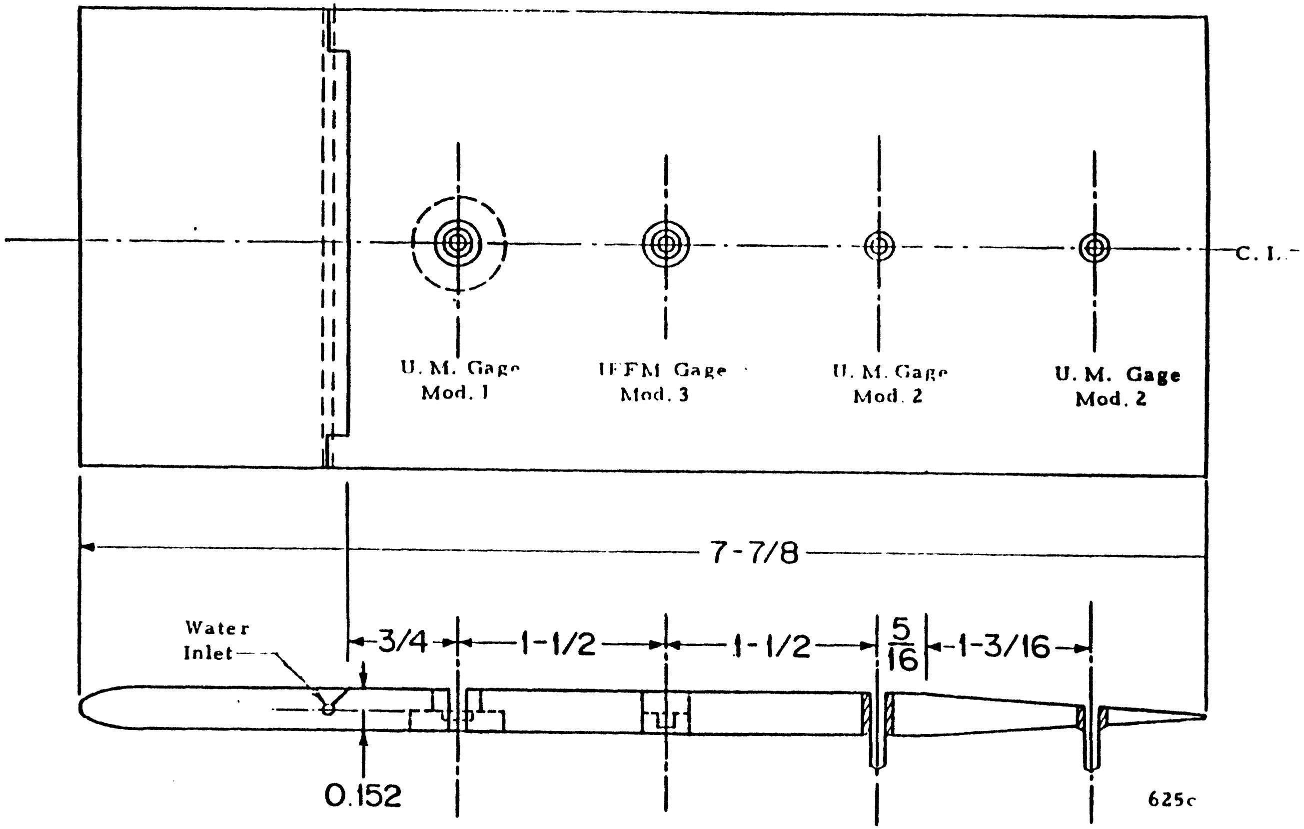

Figure 2 - Schematic of Blade with Gases

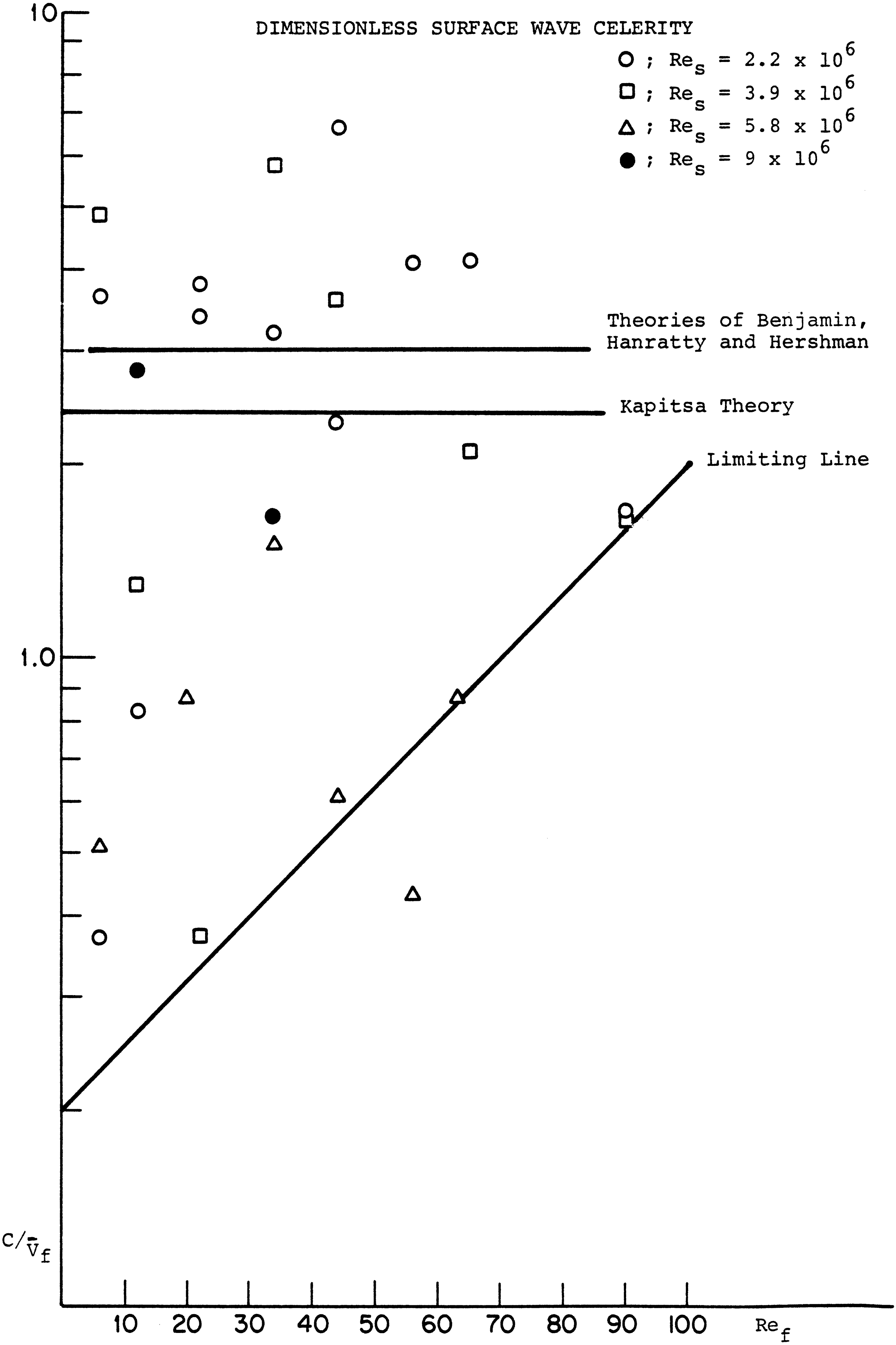
DIMENSIONLESS SURFACE WAVE CELERITY
○ ; $Re_s = 2.2 \times 10^6$
□ ; $Re_s = 3.9 \times 10^6$
△ ; $Re_s = 5.8 \times 10^6$
● ; $Re_s = 9 \times 10^6$
Theories of Benjamin, Hanratty and Hershman
Kapitsa Theory
Limiting Line
10
1.0
$C/\bar{V}_f$
10
20
30
40
50
60
70
80
90
100
Re_f

FIGURE 5

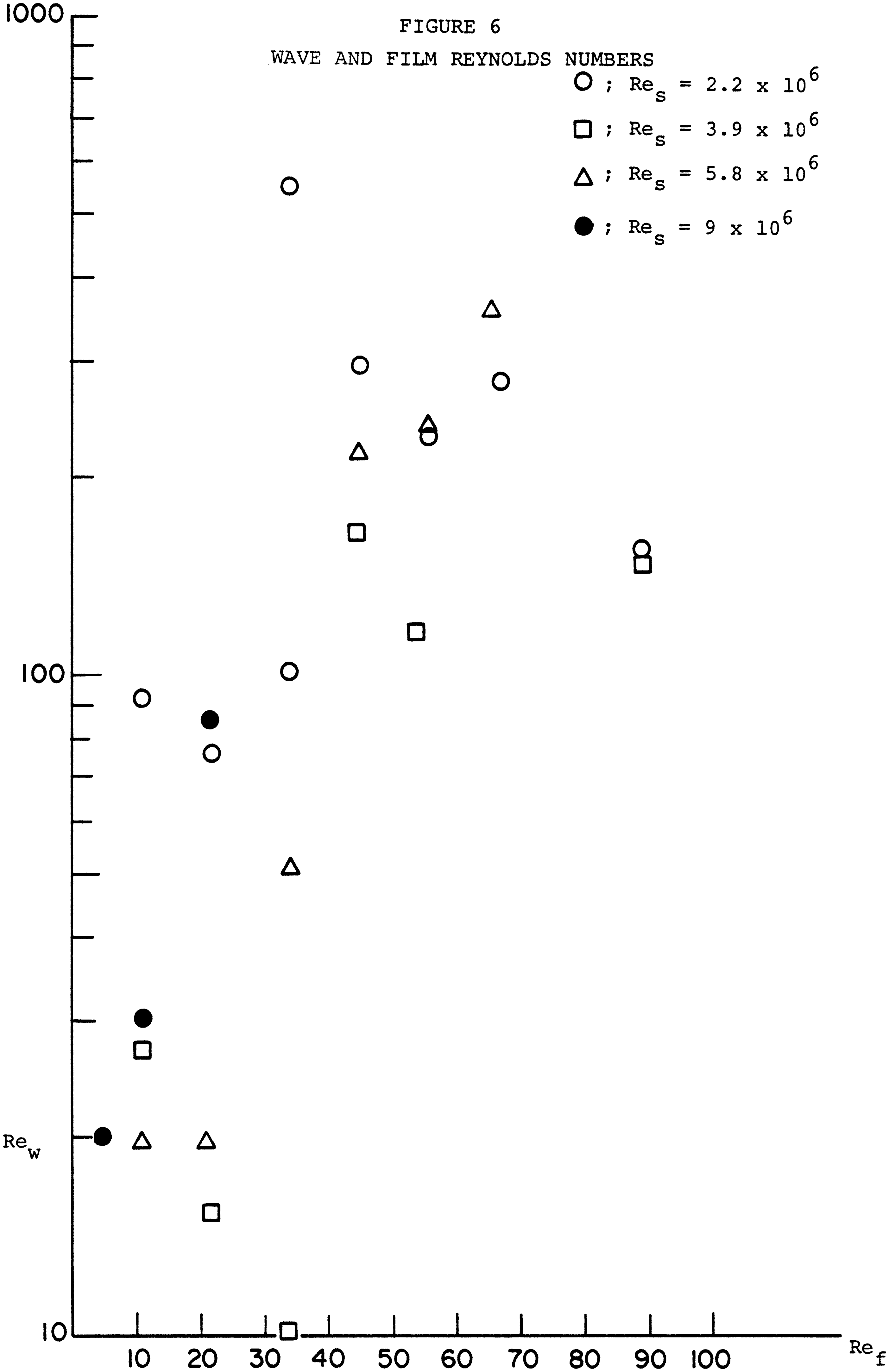

FIGURE 6

WAVE AND FILM REYNOLDS NUMBERS

FIGURE 7

FILM THICKNESS VS. V_{steam} , $\dot{Q}$ = 40 cc/min.