NOLTR 63-208

COMPARISONS OF EXPERIMENTAL AND THEORETICAL HEAT TRANSFER TO A YAWED SPHERE-CONE MODEL AT SUPERSONIC SPEEDS

6 DECEMBER 1963

NOL
UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 63-208

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AD NUMBER	(To be inserted by DDC)
CLASSIFICATION	[illegible]
	UNCLASSIFIED WHEN ENCLOSURE IS REMOVED
ORIGINATING AGENCY	Naval Ordnance Laboratory, White Oak
REPORT SERIES AND NUMBER	NOLTR 63-[illegible]
ENCLOSURE (REPORT TITLE)	Comparisons of Experimental and Theoretical Heat Transfer to a Yawed Sphere-Cone Model at Hypersonic Speeds
REPORT DATE	[illegible] December [illegible]
COG. BUWEPS CODE *(For use in BUWEPS only)*	
CONTRACT/PROJECT/WEPTASK NUMBER	[illegible]

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NOLTR 63-208

Aerodynamics Research Report No. 207

COMPARISONS OF EXPERIMENTAL AND THEORETICAL HEAT TRANSFER TO A YAWED SPHERE-CONE MODEL AT SUPERSONIC SPEEDS

by
Lionel Pasiuk

ABSTRACT: Theoretical laminar heat transfer rates to a sphere-cone model at angles of yaw up to 18° are compared with wind tunnel data measured at Mach numbers of 3.2 and 4.8. Two methods of heat transfer prediction have been chosen--the methods of Beckwith and Vaglio-Laurin. These require that the inviscid streamline pattern on the surface of the yawed sphere-cone model be known. These streamlines have been calculated from measured surface pressure distributions. The theory of Beckwith agrees reasonably well with the experimental data.

PUBLISHED OCTOBER 1964

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

6 December 1963

NOLTR 63-208

Comparisons of the Experimental and Theoretical Heat Transfer to a Yawed Sphere-Cone Model at Supersonic Speeds

This report contains the results of a project undertaken at NOL to obtain a more complete understanding of the heat transfer to blunt bodies at angles of yaw. Theoretical calculations of the compressible laminar heat transfer rates to a yawed sphere-cone model have been made, and the results are compared with experimental measurements.

The author is indebted to Dr. E. L. Harris for his solution of the streamline problem and also for his helpful comments and recommendations in the preparation of the heat transfer calculations. He also wishes to acknowledge the efforts of J. Lichter and J. R. Powers for writing the program used for the streamline and heat transfer calculations.

This work was sponsored by the Bureau of Naval Weapons under Task No. RMGA-81-034/212-1/F009-10-01.

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By direction

CONTENTS

ILLUSTRATIONS

SYMBOLS

a_*	speed of sound at $M=1$
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
H	stagnation enthalpy
h	static enthalpy
$\bar{h}$	heat transfer coefficient, $\frac{q_w}{T_{aw} - T_w}$
k	thermal conductivity
M	Mach number
Δn	distance between streamlines
p	static pressure
Pr	Prandtl number
q	heat transfer rate per unit area
R	model base radius
R_s	radius of spherical section of the model
S	distance along a meridian on the surface of the model measured from the point where the axis of symmetry intersects the surface of the spherical nose
S_c	value of S to the sphere-cone junction
T	temperature
u	velocity in the streamwise direction
v	cross flow velocity
w	defined by equation (3)
x,y,z	coordinates of orthogonal streamline coordinate system
α	angle of yaw
α_c	cone half angle

β	similarity parameter (Eq. (7))
γ	specific heat ratio, C_p/C_v
η	parameter in equation (1b)
θ_w'	enthalpy gradient parameter which is a function of β and T_w and is tabulated in reference (8)
$\theta_w',_{\beta=1}$	value of the enthalpy gradient parameter when $\beta=1$
μ	viscosity coefficient
ξ	defined in equation (1a)
ρ	density
τ	distance along a streamline measured from the aerodynamic stagnation point
ψ	roll angle, measured from the most windward streamline

Subscripts

aw	adiabatic wall condition
c	at the sphere-cone junction
e	conditions external to the boundary layer
o	stagnation value
r	some reference condition
sp	stagnation point condition
w	conditions at the wall
∞	free stream conditions

INTRODUCTION

During atmospheric flight, high speed missiles may fly at angles of yaw. Since the aerodynamic heat transfer is an important factor, it is necessary to know the effects of yaw on the heat transfer rates. These effects may be determined by experimental or theoretical means. The purpose of this report is to compare the results of calculated and measured values of the laminar heat transfer distribution on a yawed sphere-cone model.

The experimental data used for the present comparison were obtained from measurements made at the U. S. Naval Ordnance Laboratory. Measurements were made at Mach numbers of 3.2 and 4.8, at angles of yaw of 0^o, 6^o, and 18^o. The results appear in references (1) and (2).

Two theoretical solutions have been used for comparison with the experimental data. They have been developed by Beckwith (ref. (3)) and Vaglio-Laurin (ref. (4)). Essentially, Beckwith has demonstrated that for small but finite cross flows in the boundary layer the continuity equation, the streamwise momentum equation, and the energy equation are independent of the cross-flow velocity component when these are written in the inviscid streamline coordinate system. These equations are similar to the usual boundary layer equations for an axisymmetric body. Therefore, once the streamlines external to the boundary layer are known, any method applicable to a body of revolution can be used to calculate the heat transfer and skin friction over an axisymmetric body at yaw. Vaglio-Laurin used the same considerations as Beckwith except that he made two assumptions which simplified the calculation of the heat transfer. First, he assumed a cold wall and used Lees' argument of reference (5) to neglect the pressure gradient term in the boundary layer equation. Second, he took the Mach number external to the boundary layer to be small enough so that the recovery temperature could be approximated by the stagnation temperature.

Now it is stated above that the inviscid streamlines are needed in order to calculate the heat transfer. These streamlines were found using a method devised by Harris (ref. (6)). This method uses the static pressure distributions on the model's surface as input data in the solution of four differential equations which describe the inviscid flow on the surface of the yawed model.

Presented in this report are the results of the streamline calculations, the heat transfer calculations, and the comparison between the calculated and experimental heat transfer distributions.

CALCULATIONS

Streamlines

In calculating the aerodynamic heat transfer rates to the yawed sphere-cone model, one first determines the inviscid streamline pattern on the surface of the model and then calculates the heat transfer along each streamline. The orthogonal streamline coordinate system is shown in figure 1. It is generated so that the x axis is the inviscid streamline velocity vector projected on a plane tangent to the body's surface. The y axis lies in the tangent plane. The quantity τ is the distance measured along a streamline from the aerodynamic stagnation point.

The inviscid streamline pattern is found by the numerical solution of four differential equations derived by Harris (ref. (6)). For the spherical section of the model these are:

$$\frac{dS}{d\tau} = \xi \tag{1a}$$

$$\frac{d\psi}{d\tau} = \frac{\eta}{\left(R_s \sin\frac{S}{R_s}\right)^2} \tag{1b}$$

$$\frac{d\xi}{d\tau} = \frac{\eta \cos\frac{S}{R_s}}{\left(R_s \sin\frac{S}{R_s}\right)^3} - \frac{1}{\rho_e u_e^2}\left[\frac{\partial p}{\partial S} - \xi\left\{\xi\frac{\partial p}{\partial S} + \frac{\eta}{\left(R_s \sin\frac{S}{R_s}\right)^2}\,\frac{\partial p}{\partial \psi}\right\}\right] \tag{1c}$$

$$\frac{d\eta}{d\tau} = -\frac{1}{\rho_e u_e^2}\left[\frac{\partial p}{\partial \psi} - \eta\left\{\xi\frac{\partial p}{\partial S} + \frac{\eta}{\left(R_s \sin\frac{S}{R_s}\right)^2}\,\frac{\partial p}{\partial \psi}\right\}\right] \tag{1d}$$

On the surface of the cone the equations are:

$$\frac{dS}{d\tau} = \xi \tag{2a}$$

$$\frac{d\psi}{d\tau} = \frac{\eta}{w^2} \qquad (2b)$$

$$\frac{d\xi}{d\tau} = \frac{\eta^2 \sin\alpha_c}{w^3} - \frac{1}{\rho_e u_e^2}\left[\frac{\partial p}{\partial S} - \xi\left\{\xi\frac{\partial p}{\partial S} + \frac{\eta}{w^2}\frac{\partial p}{\partial \psi}\right\}\right] \qquad (2c)$$

$$\frac{d\eta}{d\tau} = -\frac{1}{\rho_e u_e^2}\left[\frac{\partial p}{\partial \psi} - \eta\left\{\xi\frac{\partial p}{\partial S} + \frac{\eta}{w^2}\frac{\partial p}{\partial \psi}\right\}\right] \qquad (2d)$$

where

$$w = (S - S_c)\sin\alpha_c + R_s \cos\alpha_c \qquad (3)$$

Equations (1) and (2) are derived from the inviscid momentum equations. For a given streamline, the four dependent variables S, ψ, ξ, and η are obtained as a function of τ from the numerical solution of equations (1) and (2) on the IBM 7090 computer. The computer program used is described in reference (7).

As can be seen in equations (1) and (2), the values for $\partial p/\partial s$ and $\partial p/\partial\psi$ must be known. These are found by differentiating curve fits to the experimental pressure data found in references (1) and (2). Other flow properties are calculated from this static pressure data assuming an isentropic expansion of the flow from the aerodynamic stagnation point.

The calculation for each streamline is started at some point on a small initial circle, the center of which is at the aerodynamic stagnation point (see fig. 1). It is assumed that the streamline flow is radial from the stagnation point to the initial circle. Each streamline is defined by the angle the streamline makes with the most windward streamline at the stagnation point.

Heat Transfer

The laminar heat transfer rates are calculated from the theories of Beckwith (ref. (3)) and Vaglio-Laurin (ref. (4)). The equation for the heat transfer distribution given by Beckwith is

$$\frac{\bar{h}}{\bar{h}_r} = \left[\frac{p_e}{p_r}\left(\frac{h}{H_e}\right)_r \left(\frac{H}{h}\right)_e \frac{\beta_r}{\beta} \frac{du_e/d\tau}{(du_e/d\tau)_r}\right]^{\frac{1}{2}} \left(\frac{\theta'_w}{\theta'_{w,\beta=1}}\right) \left(\frac{\theta'_{w,\beta=1}}{\theta'_w}\right)_r \tag{4}$$

where $\bar{h}$ is the heat transfer coefficient. Because C_p varies only about 0.3 percent for the temperature range of the experimental data, it is taken as a constant in equation (4). The reference point, r, of the body is taken to be the stagnation point, sp. Since it is assumed that the flow is adiabatic along the external streamlines, H_e is also constant and equation (4) becomes

$$\frac{\bar{h}}{\bar{h}_{sp}} = \left[\frac{\rho_e}{\rho_{sp}} \frac{\beta_{sp}}{\beta} \frac{(du_e/d\tau)}{(du_e/d\tau)_{sp}}\right]^{\frac{1}{2}} \left(\frac{\theta'_w}{\theta'_{w,\beta=1}}\right) \left(\frac{\theta'_{w,\beta=1}}{\theta'_w}\right)_{sp} \tag{5}$$

The terms in this equation are as follows:

$$T_{aw} = T_e + Pr^{\frac{1}{2}}\left(T_o - T_e\right) \tag{6}$$

The equation for β is

$$\beta = \frac{2\frac{du_e}{d\tau}}{\frac{p_e}{p_{sp}} u_e^2 \frac{T_e}{T_o}(\Delta n)^2} \int_o^\tau \frac{p_e}{p_{sp}} u_e (\Delta n)^2 \, d\tau \tag{7}$$

At the aerodynamic stagnation point, $\beta_{sp} = 0.5$. The velocity and velocity gradient are calculated from the inviscid momentum equation in the streamline direction, and the resulting equations are

$$\frac{du_e}{d\tau} = -\frac{1}{\rho_e u_e} \frac{dp_e}{d\tau} \tag{8}$$

and

$$u_e = a_*\left\{\frac{\gamma + 1}{\gamma - 1}\left[1 - \left(\frac{p_e}{p_{sp}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{9}$$

At the aerodynamic stagnation point, equation (8) is indeterminate, and the expression for the velocity gradient which is obtained from modified Newtonian flow is

$$\left(\frac{du_e}{d\tau}\right)_{sp} = \frac{a_*}{R_s}\left[\left(\frac{1 + \gamma}{\gamma}\right)\left(1 - \frac{p_\infty}{p_{sp}}\right)\right]^{\frac{1}{2}} \tag{10}$$

The parameter $\theta_w'/\theta_{w,\beta=1}'$ is a function of β and h_w/H_e and can be found in reference (8). Finally, the term Δn describes the spreading of the streamlines, and on the spherical section of the body is taken as

$$\Delta n = R_s \sin\frac{\tau}{R_s} \tag{11}$$

On the conical section of the body, Δn at a given point on a given streamline may be found from the numerical solution to equations (2a) to (2d). The value of Δn was approximated by the normal distance from the given point to an adjacent streamline.

As suggested by Beckwith, the absolute level of heating was established by using the heat transfer equation for a three-dimensional stagnation point derived by Reshotko (ref. (9)). For C_p = constant the equation is

$$\bar{h}_{sp} = k_w \theta_w' Pr^{0.4}\left[\frac{\rho_w}{\mu_w}\left(\frac{du_e}{d\tau}\right)_{sp}\right]^{\frac{1}{2}} \tag{12}$$

The equation for the laminar compressible heat transfer rates as given by Vaglio-Laurin in reference (4) is

$$q_w = 0.47Pr^{-2/3}\,(H_{o,e} - H_w)\frac{\rho_e\mu_e u_e \Delta n}{\left[2\int_0^\tau \rho_e\mu_e u_e (\Delta n)^2 d\tau\right]^{\frac{1}{2}}} \tag{13}$$

At the stagnation point, the limiting value of equation (13) is

$$(q_w)_{sp} = 0.47 Pr^{-2/3} (H_{o,e} - H_w)_{sp} \left[2 \rho_{sp} \mu_{sp} \left(\frac{du_e}{d\tau} \right)_{sp} \right]^{\frac{1}{2}} \qquad (14)$$

For C_p = constant,

$$\frac{\bar{h}}{\bar{h}_{sp}} = \frac{(T_o - T_w)}{(T_{aw} - T_w)} \frac{\frac{\rho_e}{\rho_{sp}} \frac{\mu_e}{\mu_{sp}} u_e \Delta n}{2 \left[\left(\frac{du_e}{d\tau} \right)_{sp} \int_o^\tau \frac{\rho_e}{\rho_{sp}} \frac{\mu_e}{\mu_{sp}} u_e (\Delta n)^2 d\tau \right]^{\frac{1}{2}}} \qquad (15)$$

The viscosity ratio from Sutherland's viscosity law is

$$\frac{\mu_e}{\mu_{sp}} = \left(\frac{T_e}{T_o} \right)^{3/2} \left(\frac{T_o + 110.4}{T_e + 110.4} \right) \qquad (16)$$

where the temperatures are in degrees Kelvin.

Equations (5) and (15) were solved on the IBM 7090 digital computer.

RESULTS

Streamlines

Calculations of the streamlines and heat transfer have been made for the following six conditions:

Table 1

	M	α	p_o	T_o
1	3.2	0°	1210 mm Hg	335°K
2	3.2	6°	980 mm Hg	318°K
3	3.2	18°	980 mm Hg	318°K
4	4.8	0°	2220 mm Hg	320°K
5	4.8	6°	2090 mm Hg	320°K
6	4.8	18°	2090 mm Hg	320°K

These are the conditions for which the experimental heat transfer data are available (T_w/T_o varies from 0.7 to 0.8). The experimental pressure and heat transfer data of conditions 1, 4, and 5 were taken from reference (1), whereas the experimental pressure and heat transfer data of conditions 2, 3, and 6 were taken from reference (2).

Each streamline calculation was started on an initial circle with $\tau/R=0.205$. From the initial circle to the sphere-cone junction, the streamline follows a great circle path.

The inviscid streamline pattern over the conical section of the sphere-cone model is plotted on figures 2a, b, c, and d for $\alpha=6^{\circ}$ and 18°, and $M=3.2$ and 4.8. Pressure gradients along the surface and normal to the streamline velocity vector cause the streamlines to curve toward the low pressures. There appears to be very little difference in the pattern of the external streamlines between the $M=3.23$ and $M=4.83$ at the same yaw angle. The curvature of the streamlines at $\alpha=18^{\circ}$ is somewhat greater than at $\alpha=6^{\circ}$.

Heat Transfer

The theoretical stagnation point heat transfer coefficient, $\bar{h}_{sp}$, has been calculated from equations (12) and (14), and compared with corresponding experimental values in Table 2 for the six conditions listed in Table 1. The figures in parentheses in Table 2 give the deviations from the experimental value.

Table 2

Stagnation point heat transfer coefficient

$\bar{h}_{sp}$, Btu/ft^2-sec-$^{\circ}$K

	Eq. 12	Eq. 14	Experimental
1	.0257(-13%)	.0236(-20%)	.0295
2	.0228(-10%)	.0209(-18%)	.0254
3	.0228(-13%)	.0209(-20%)	.0263
4	.0176(+17%)	.0161(+7%)	.0151
5	.0170	.0156	not available
6	.0163(-17%)	.0150(-23%)	.0196

In general, the predictions of equations (12) and (14) are somewhat lower than the experimental values. In the presentation of the data in figures 3 through 11, the experimental stagnation point heat transfer coefficient was used to normalize the experimental data.

Figures 3 through 11 show the comparison between the calculated and experimental heat transfer data. In general, the heat transfer distributions calculated using the theory of Beckwith (ref. (3)) are in good agreement with the experimental ones. In the region of the stagnation point ($0<\frac{S}{R}<0.3$), there are some variations of the experimental heat transfer from the theory. For example, on figures 3 through 4 in the region $0<\frac{S}{R}<0.3$, the experimental heat transfer data are from 0 percent to 20 percent lower than predicted by Beckwith's theory. The experimental heat transfer distributions on the conical section of the body for $\alpha=0^{\circ}$ and on the most windward streamline ($\psi=0$) of the angle of yaw data are in good agreement with the theory of Beckwith.

Figures 6 and 7 are plots of heat transfer versus S/R for $\psi=45^{\circ}$. The experimental heat transfer data are from 0 percent to 20 percent lower than the theory of Beckwith on the spherical section of the model, and on the conical section the experimental data are from 2C percent higher to 50 percent lower than the Beckwith theory.

Heat transfer versus ψ for constant values of S/R=1.018 and 1.516 are shown on figures 8 through 11. Figures 8a, 9a, and 9b show good agreement between the experimental heat transfer rates and those given by Beckwith's theory. The experimental heat transfer rates are 13 to 20 percent lower in figure 8b, 20 percent higher in figure 10a, 20 to 35 percent lower in 9b, up to 30 percent higher in figure 11a and up to 20 percent higher in figure 11b than Beckwith's theory.

As can be seen in figures 3 through 11, the heat transfer coefficients predicted by Vaglio-Laurin are as much as 70 percent higher than Beckwith's values. It should be stated that the experimental data were not obtained under the conditions of a cold wall and low Mach numbers outside the boundary layer as required in his theory. The experimental data were measured with values of T_w/T_O between 0.7 and 0.8, and the local Mach numbers reached values as high as 3.0. In the equation which Vaglio-Laurin gives for the heat transfer rate, the term (T_O-T_w) is used instead of the term $(T_{aw}-T_w)$ used in the Beckwith heat transfer equation. This is responsible for approximately 70 percent of the difference between the two theories. However, the other 30 percent of the difference is due to the omission of the effect of the pressure gradient in the Vaglio-Laurin heat transfer equation.

Cross Flow

The factor that makes a laminar boundary layer on a yawed sphere-cone body different than on an axisymmetric body at zero yaw is the cross flow velocity components that exist. A schematic diagram illustrating how the streamwise and cross-flow velocity components in a three-dimensional laminar boundary layer might look is given in figure 1.

Since the theory of Beckwith is applicable when the cross-flow velocities are small, it would be of interest to know what the criterion for small cross-flow velocities is, whether they exist under the conditions at which these calculations were made, and how large an effect they may have on the heat transfer.

The criterion for small cross flow which is given in reference (3) is $(\frac{v}{u})^2_{max} << 1$. At any particular point along the streamline, $(\frac{v}{u})_{max}$ is the maximum value of the ratio of the cross-flow velocity to the streamwise velocity within the boundary layer. Calculations of $(\frac{v}{u})^2_{max}$ along two different streamlines have been made using the equations in reference (3). The results are plotted in figure 12a as $(\frac{v}{u})^2_{max}$ versus τ/R for a streamline on the sphere-cone model at $M=4.8$, $\alpha=6^o$ and at $M=4.8$, $\alpha=18^o$. The locations of the two streamlines is plotted in figure 12b and are shown as broken lines in figures 2b and 2d. As can be seen in figure 12a, the value of $(\frac{v}{u})^2_{max}$ reaches a maximum value of 0.3 for $\alpha=6^o$, whereas for $\alpha=18^o$, $(\frac{v}{u})^2_{max}$ reaches a maximum value of 4.0. Even though the conditions for small cross flow are exceeded for these particular calculations, the heat transfer rates calculated using reference (3) may not necessarily be too much in error. For example, in reference (3), heat transfer calculations were made for a yawed infinite cylinder, and even though the parameter $(\frac{v}{u})^2_{max}$ went from 0 to 4, there was no error greater than 15 percent between the small cross-flow results and the exact heat transfer rates. In order to determine whether the experimental data show any increase in heat transfer rates in the regions of high cross-flow velocities, figure 13 is presented. This figure gives a plot of the ratio of experimental heat transfer coefficients and those from the theory of Beckwith versus ψ for constant values of S/R. The data are for the case where $M=4.8$, $\alpha=18^o$. As can be seen in this figure, at $S/R=0.65$, the experimental data are slightly lower than the theory. At $S/R=1.018$ and 1.267, the theory and experiment agree rather well. But when $S/R>1.267$ and $\psi>0^o$, the experimental heat transfer coefficients are higher than the theory. Now the cross-flow velocities are zero on the windward streamline ($\psi=0^o$) and on the spherical section ($S/R<0.52$) of the body, whereas on the conical section, where $\psi>0^o$ and $S/R>0.52$, the cross-flow velocities are no longer zero. Since the scatter of the experimental heat transfer coefficients is rather high on the conical section of the body (approximately ± 15 percent), it is difficult to obtain qualitatively what the effect of cross flow is on the experimental data. Nevertheless, it is apparent from the data of figure 13 that the small cross-flow theory of Beckwith predicts heat transfer coefficients that are within 15 percent of the experimental values, even though the criterion of small cross flow is not met everywhere on the cone.

CONCLUSIONS

A comparison has been made between the experimental and theoretical compressible laminar heat transfer rates to a yawed sphere-cone body. It has been demonstrated that the streamlines on the surface of this sphere-cone body can be calculated if the static pressure distribution on the surface of the body is known. Heat transfer distributions along the streamlines were calculated by applying methods given by Beckwith and Vaglio-Laurin.

The method of Beckwith predicts compressible laminar heat transfer distributions that are in good agreement with the experimental values in the region of zero cross-flow velocities and to within approximately 15 percent in the region of high cross-flow velocities for the range of conditions for which experimental data were available.

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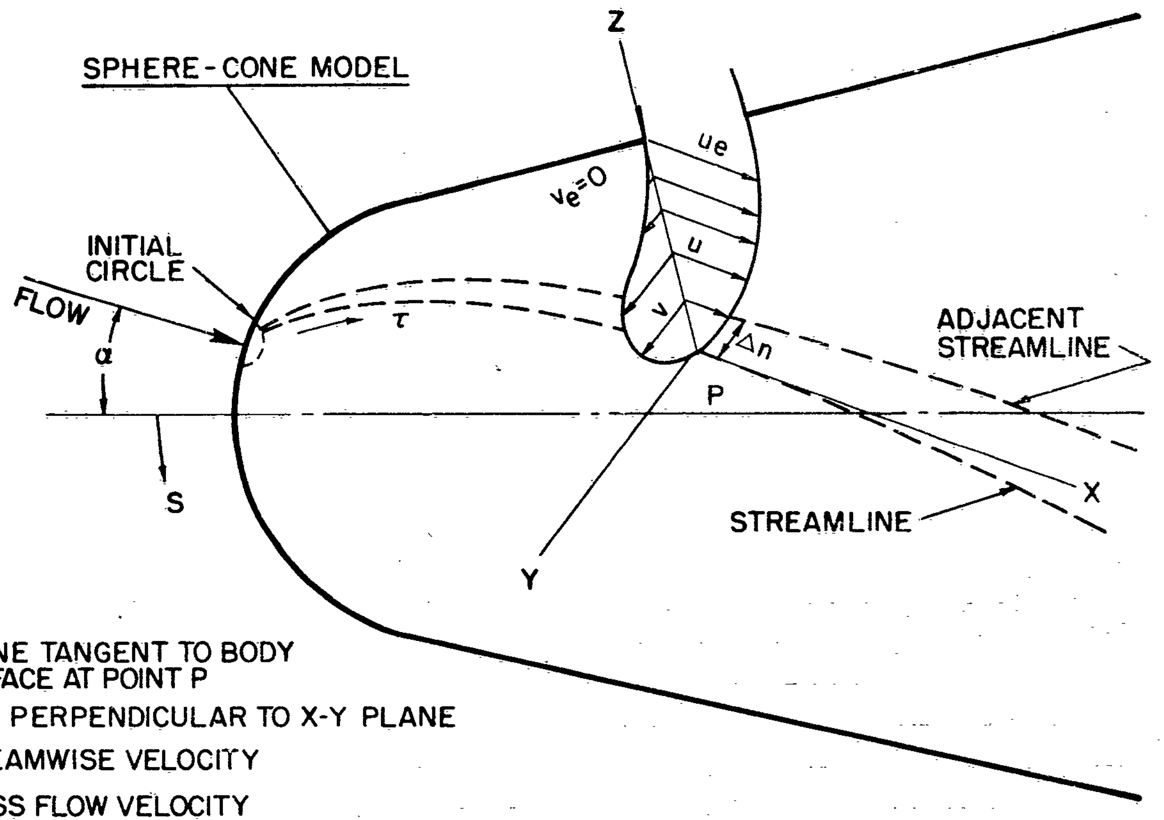


X-Y PLANE TANGENT TO BODY SURFACE AT POINT P

Z AXIS PERPENDICULAR TO X-Y PLANE

u – STREAMWISE VELOCITY

v - CROSS FLOW VELOCITY

τ - STREAMLINE LENGTH

FIGURE I THE COORDINATE SYSTEM OF THE MODEL AND STREAMLINES

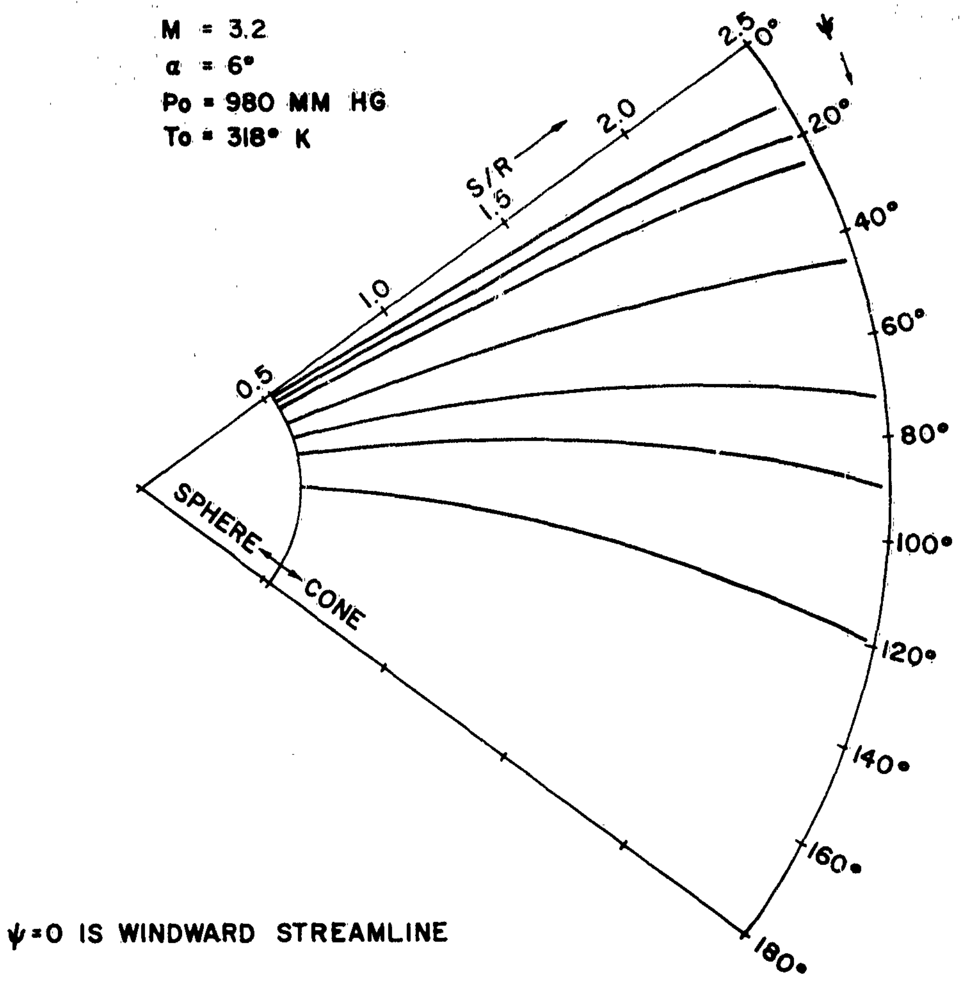
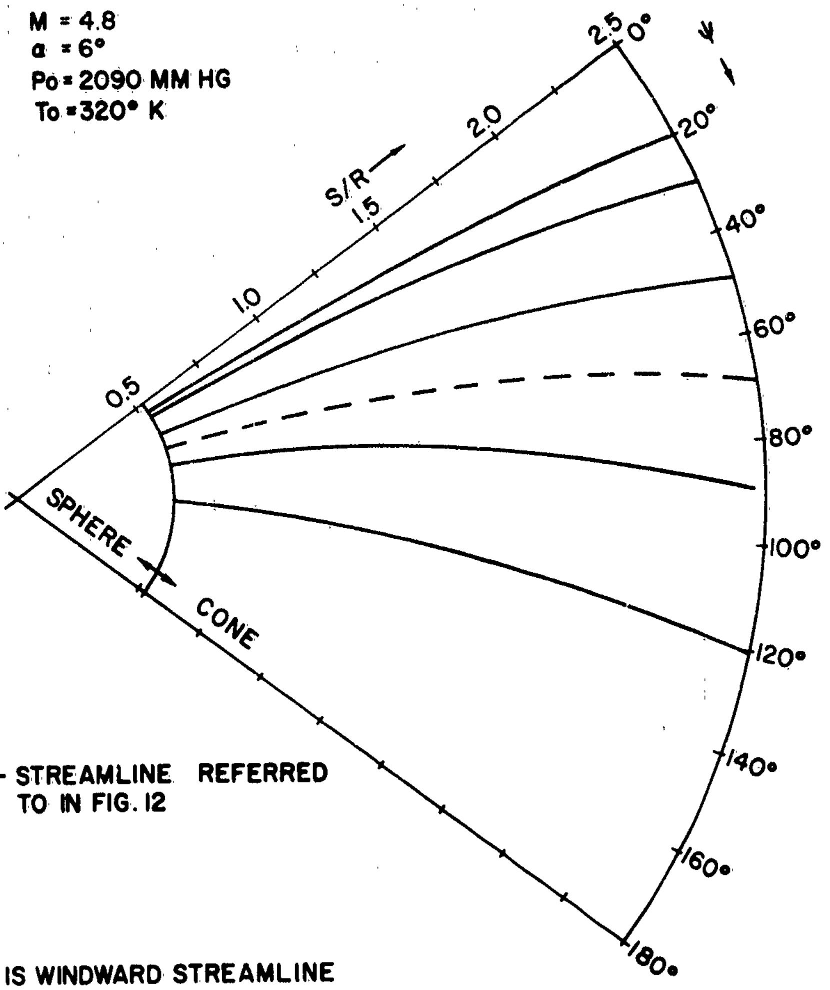


FIGURE 2(a) CALCULATED STREAMLINE PATTERN ON THE CONICAL SECTION OF THE SPHERE-CONE MODEL



– – – – STREAMLINE REFERRED TO IN FIG. 12

ψ = 0 IS WINDWARD STREAMLINE

FIGURE 2(b)

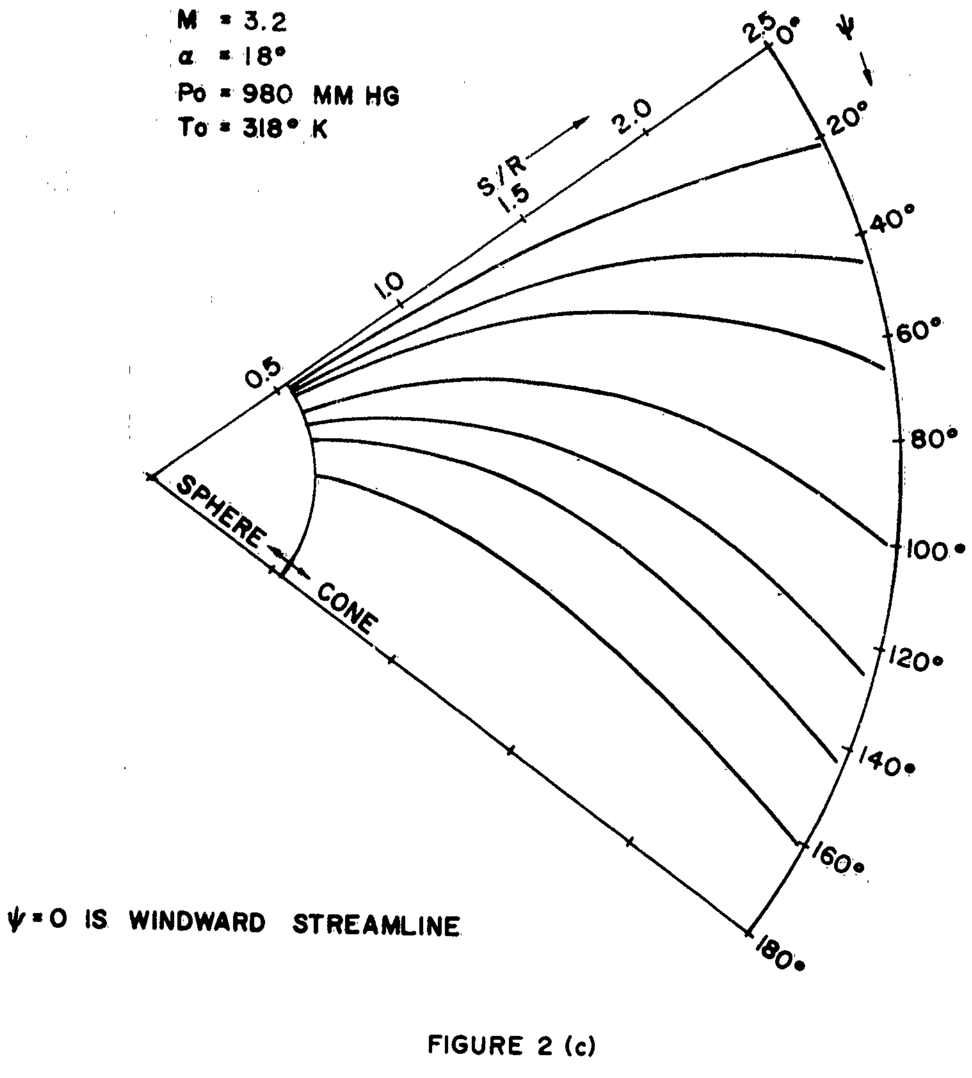

M = 3.2
α = 18°
Po = 980 MM HG
To = 318° K
S/R
0.5
1.0
1.5
2.0
2.5
ψ
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
SPHERE
CONE
ψ = 0 IS WINDWARD STREAMLINE

FIGURE 2 (c)

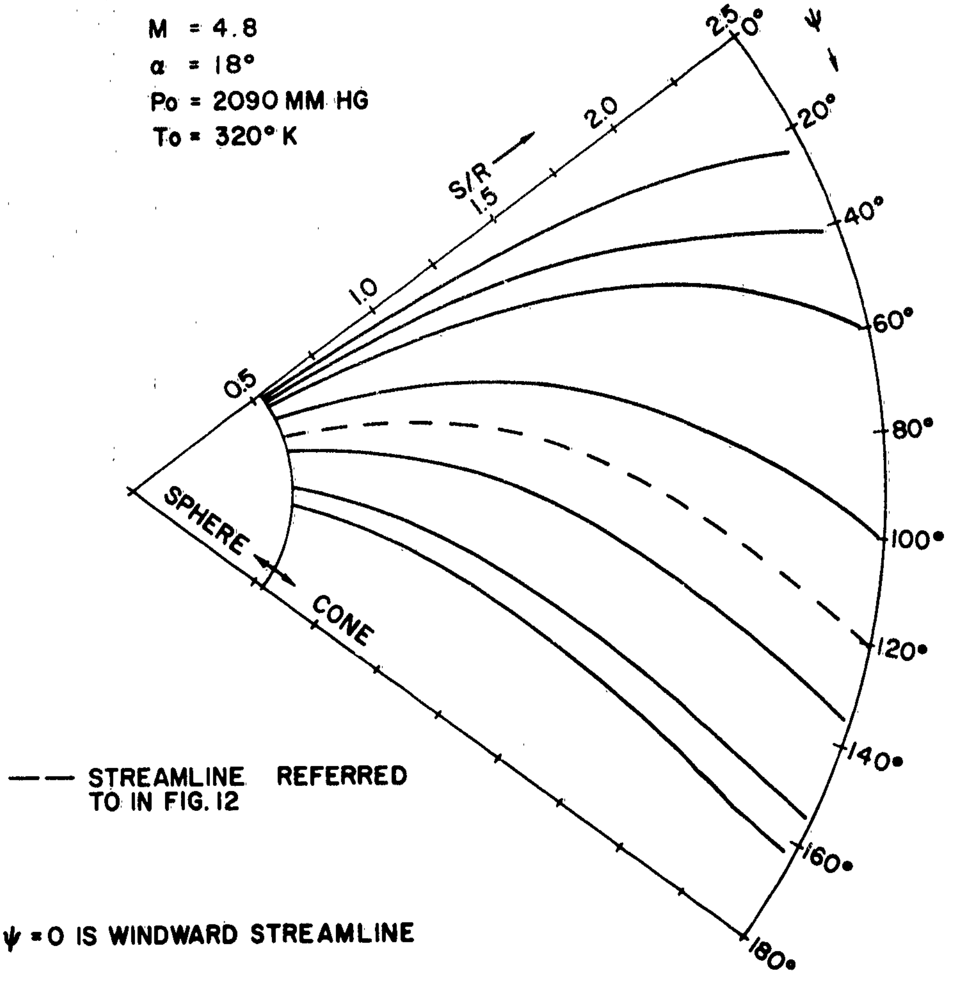

M = 4.8
α = 18°
Po = 2090 MM HG
To = 320° K
S/R
0.5
1.0
1.5
2.0
2.5
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
ψ
SPHERE
CONE
— — STREAMLINE REFERRED TO IN FIG. 12
ψ = 0 IS WINDWARD STREAMLINE

FIGURE 2 (d)

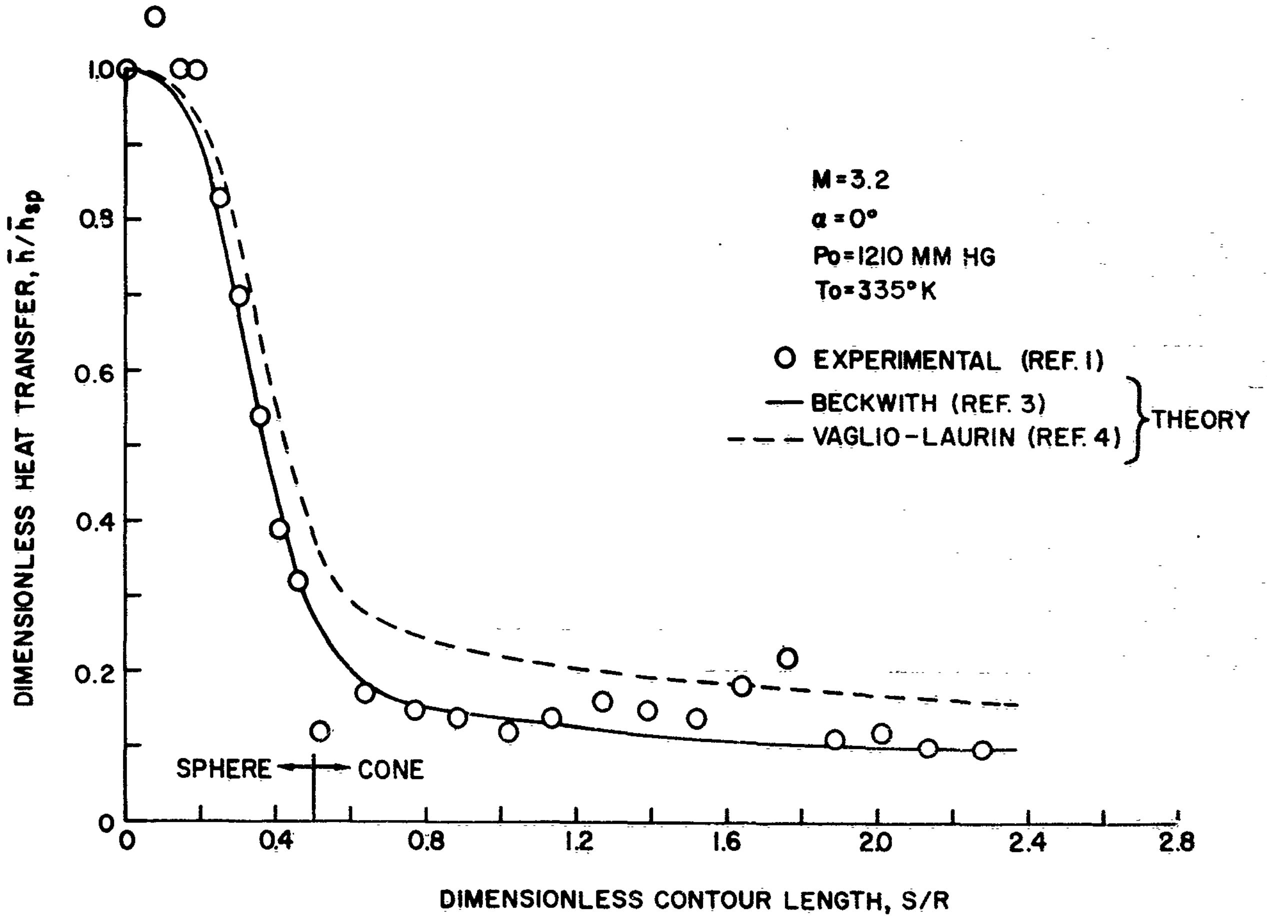


FIGURE 3 (a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS S/R AT $\alpha=0°$

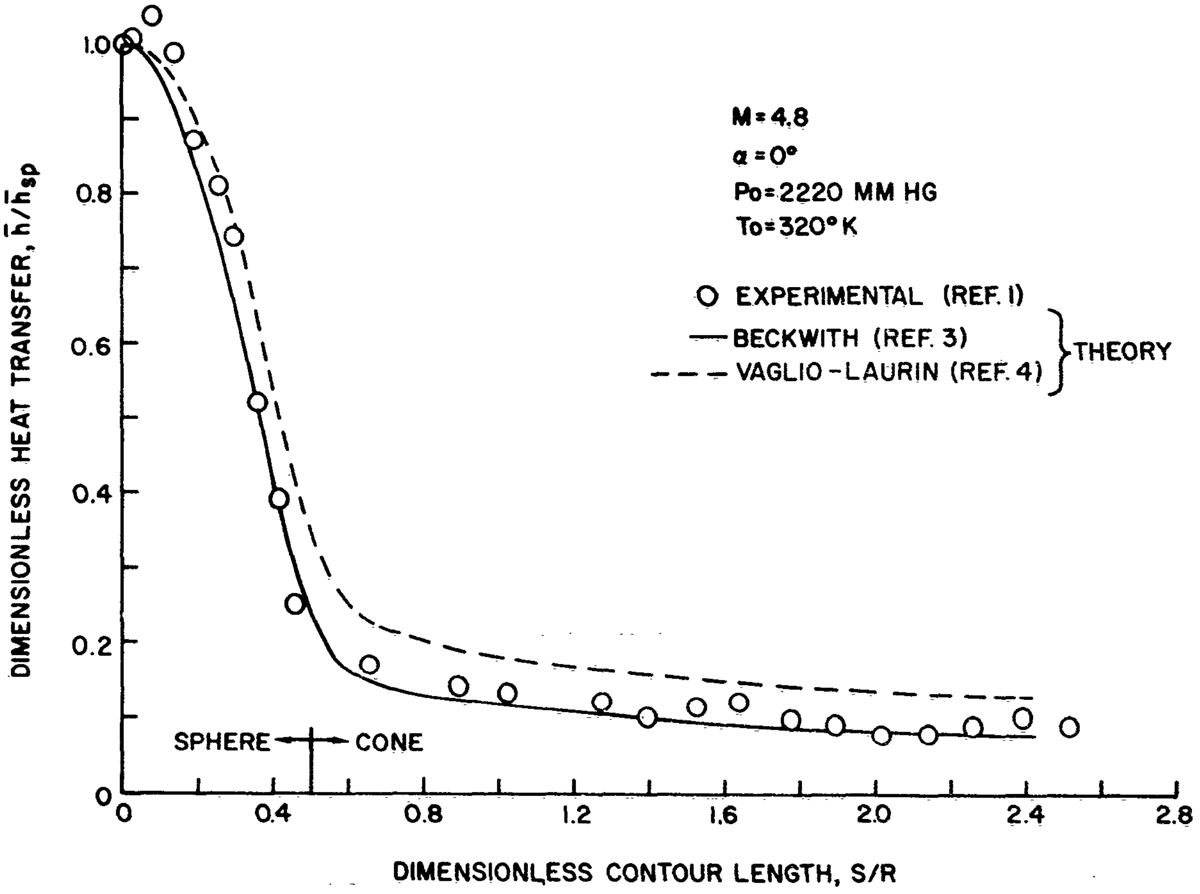

M = 4.8
α = 0°
Po = 2220 MM HG
To = 320° K
○ EXPERIMENTAL (REF. I)
— BECKWITH (REF. 3)
– – – VAGLIO-LAURIN (REF. 4)
THEORY
SPHERE
CONE
DIMENSIONLESS HEAT TRANSFER, $\bar{h}/\bar{h}_{sp}$
DIMENSIONLESS CONTOUR LENGTH, S/R
0
0.2
0.4
0.6
0.8
1.0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8

FIGURE 3 (b)

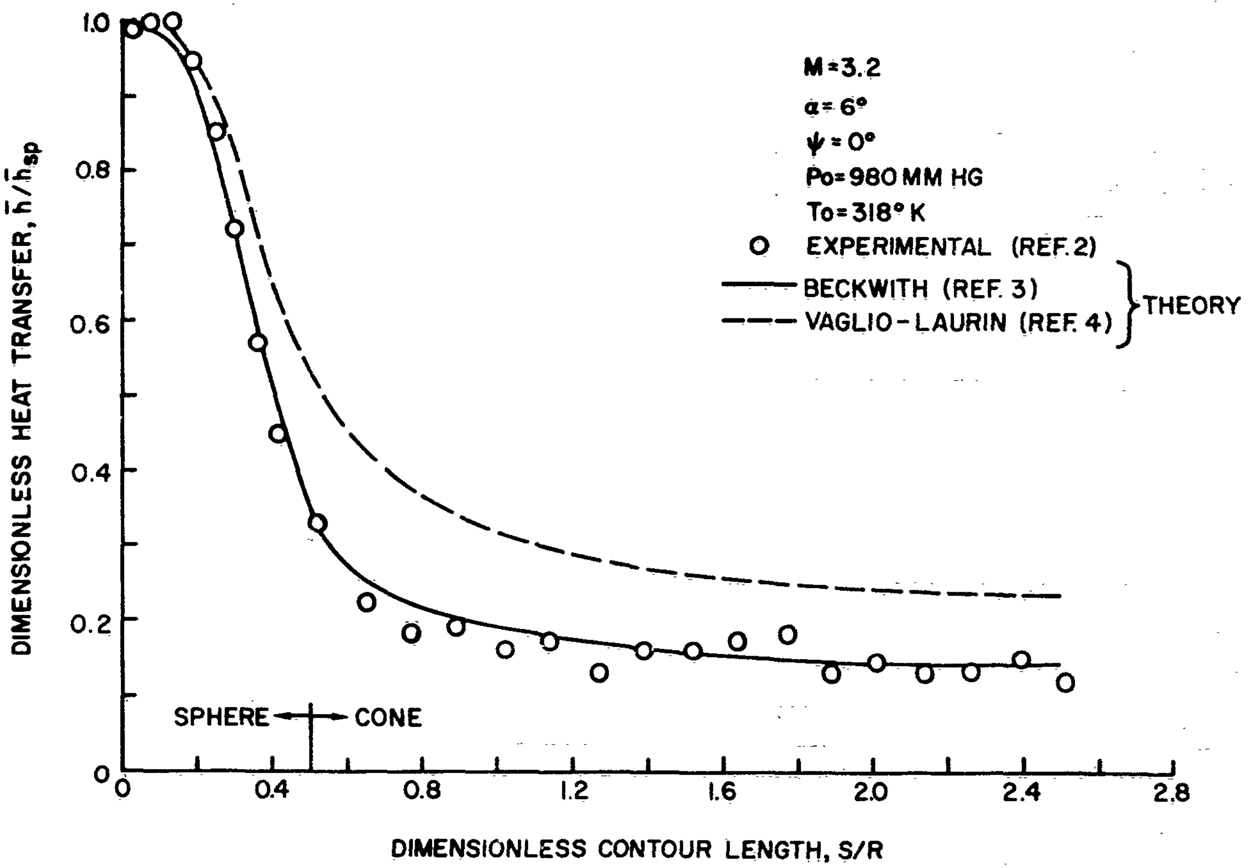


FIGURE 4 (a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS S/R AT $\alpha = 6°$, $\psi = 0°$

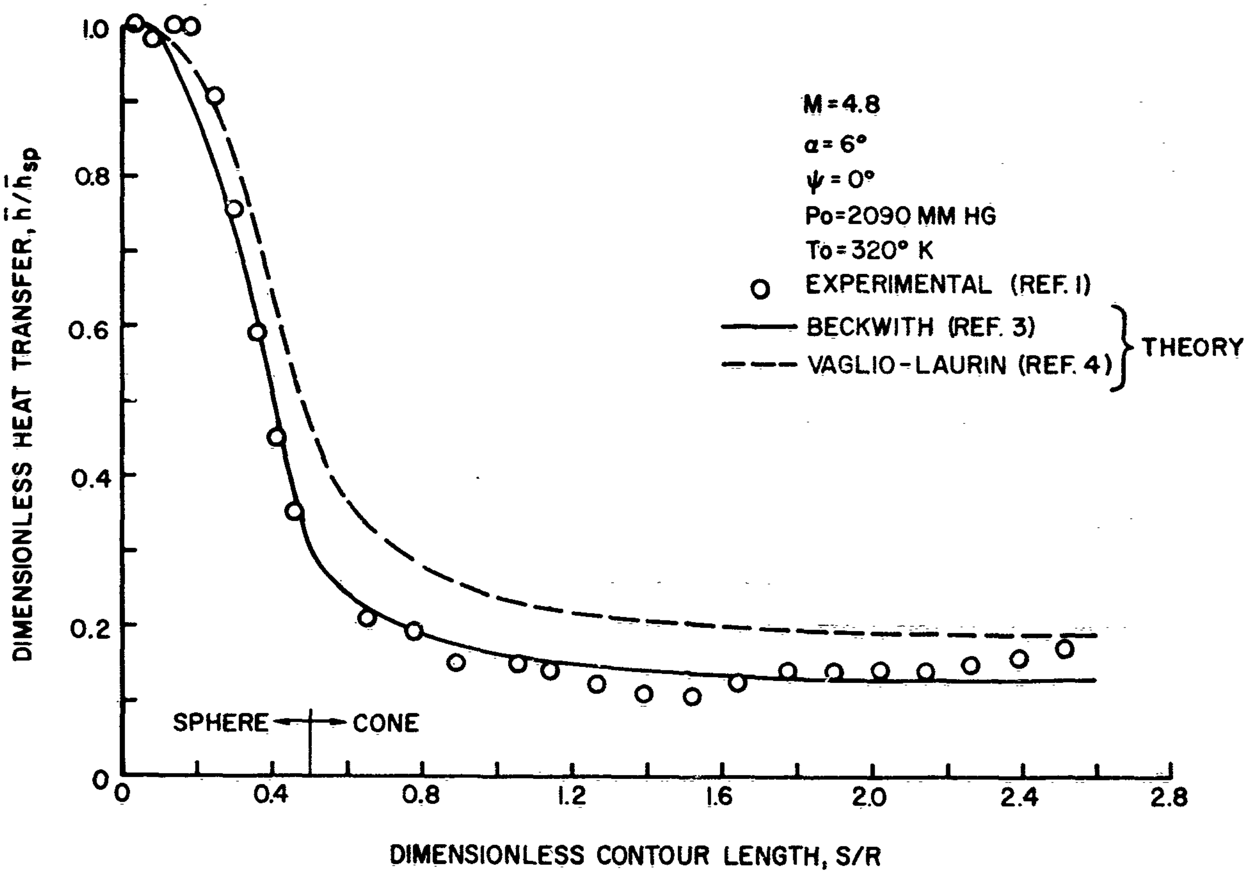

M=4.8
α=6°
ψ=0°
Po=2090 MM HG
To=320° K
○ EXPERIMENTAL (REF. I)
—— BECKWITH (REF. 3)
– – – VAGLIO-LAURIN (REF. 4)
THEORY
DIMENSIONLESS HEAT TRANSFER, h̄/h̄sp
1.0
0.8
0.6
0.4
0.2
0
SPHERE
CONE
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
DIMENSIONLESS CONTOUR LENGTH, S/R

FIGURE 4(b)

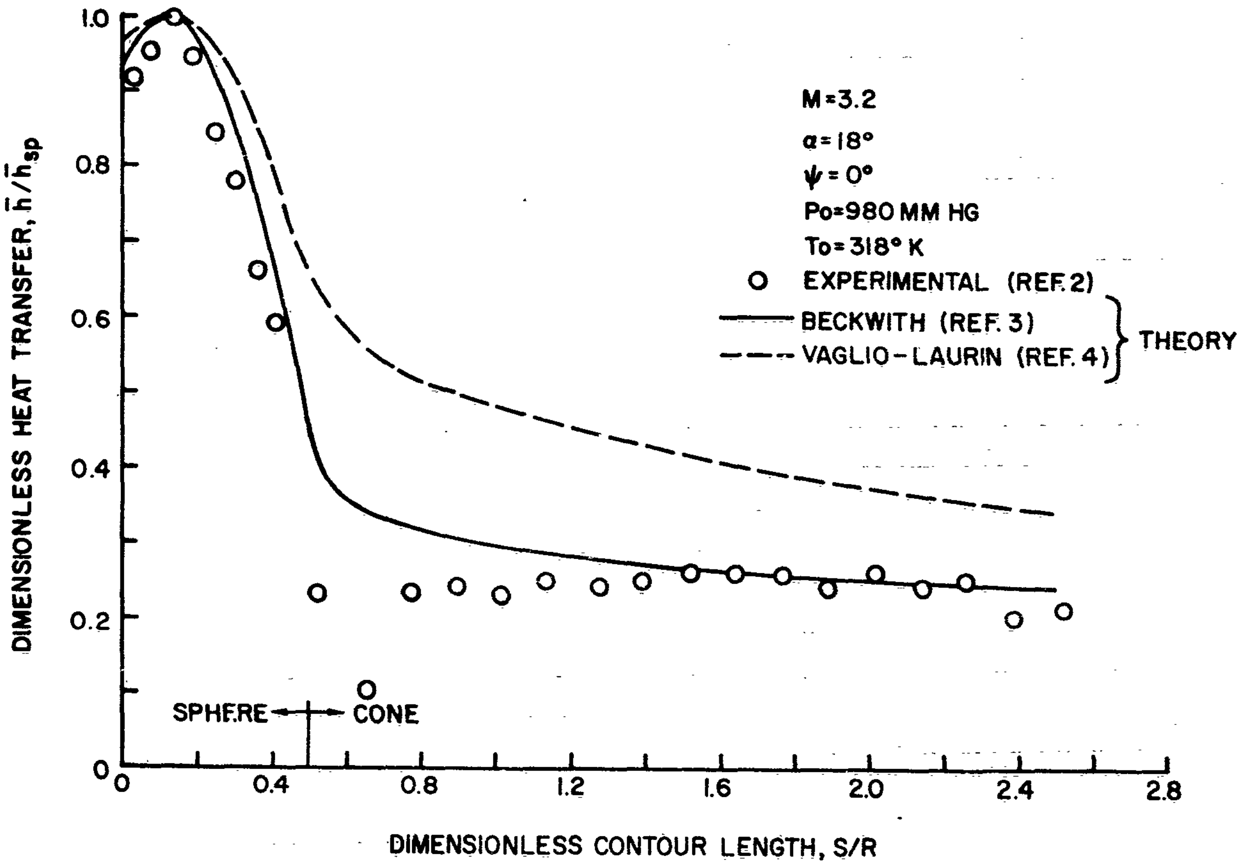


FIGURE 5 (a)—COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS S/R AT $\alpha = 18°$, $\psi = 0°$

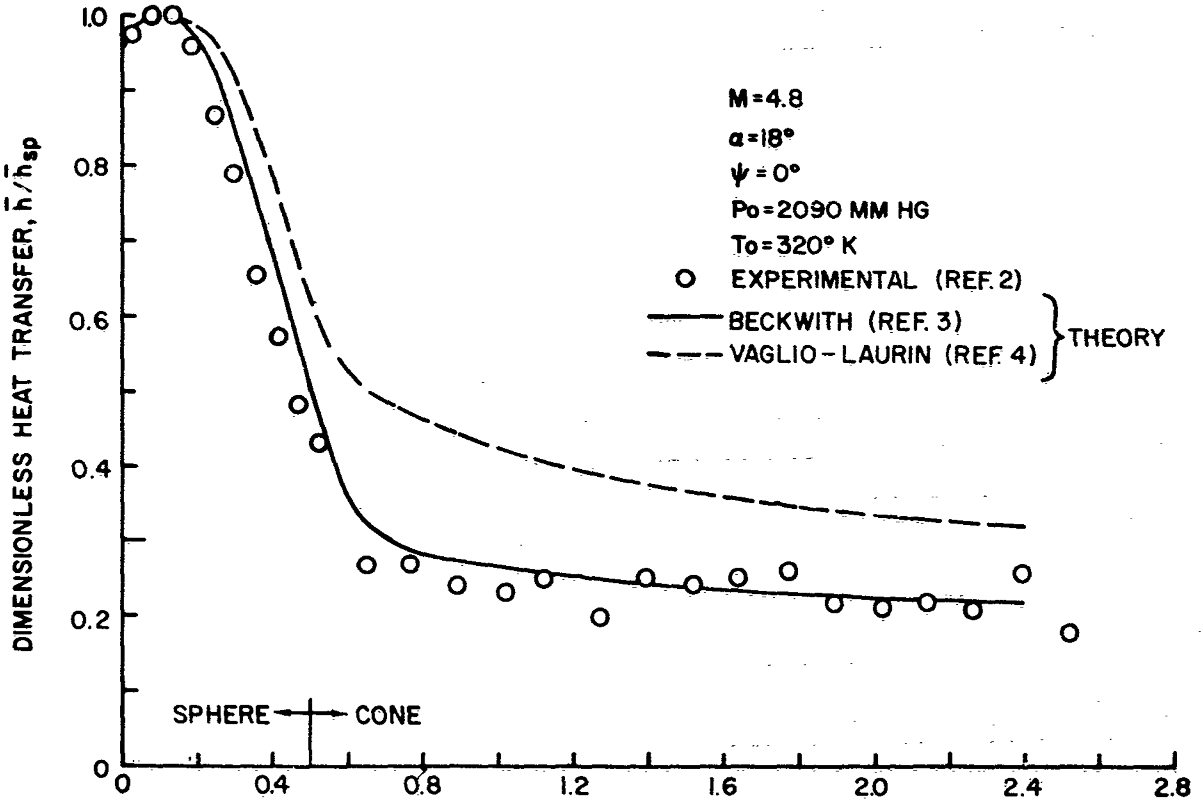

1.0
0.8
0.6
0.4
0.2
0
DIMENSIONLESS HEAT TRANSFER, $\bar{h}/\bar{h}_{sp}$
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
DIMENSIONLESS CONTOUR LENGTH, S/R
SPHERE ← → CONE
M=4.8
α=18°
ψ=0°
Po=2090 MM HG
To=320° K
○ EXPERIMENTAL (REF. 2)
—— BECKWITH (REF. 3)
– – – VAGLIO-LAURIN (REF. 4)
THEORY

FIGURE 5(b)

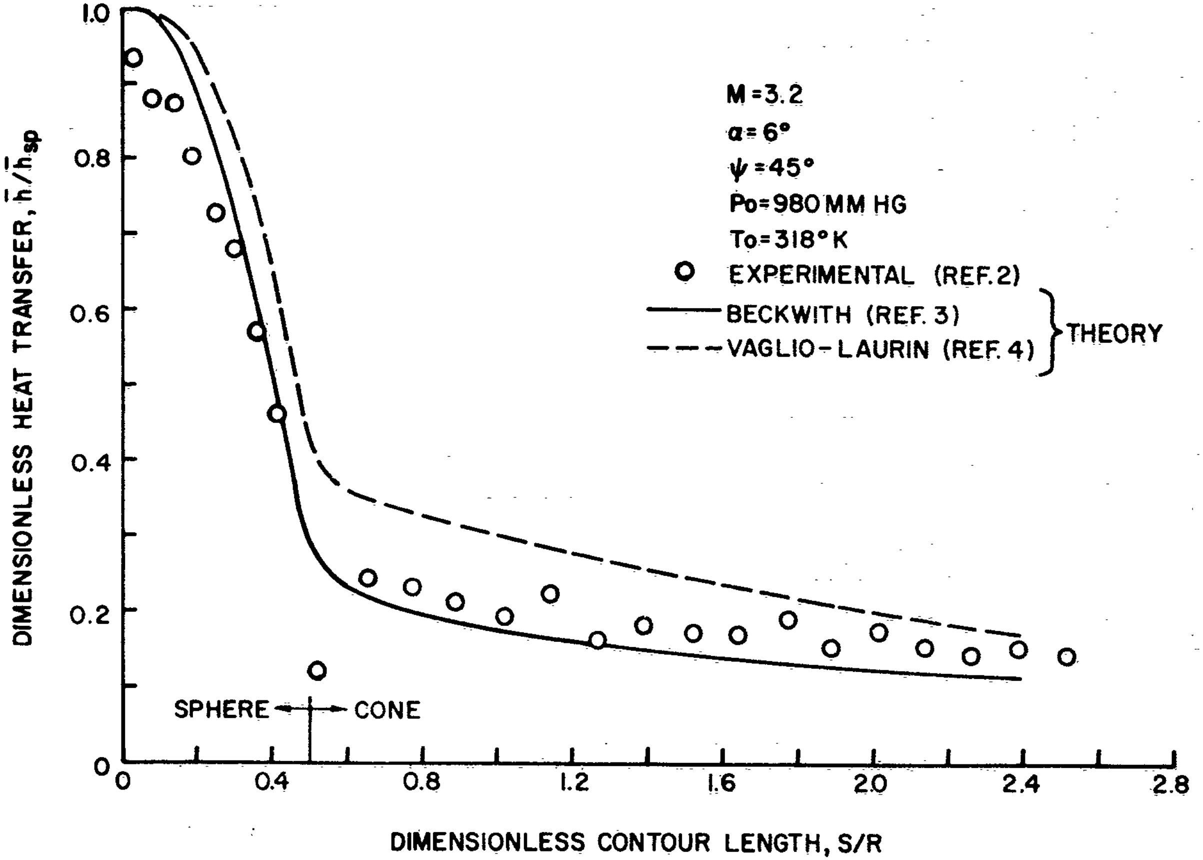


FIGURE 6 (a)—COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS S/R AT $\alpha = 6°$, $\psi = 45°$

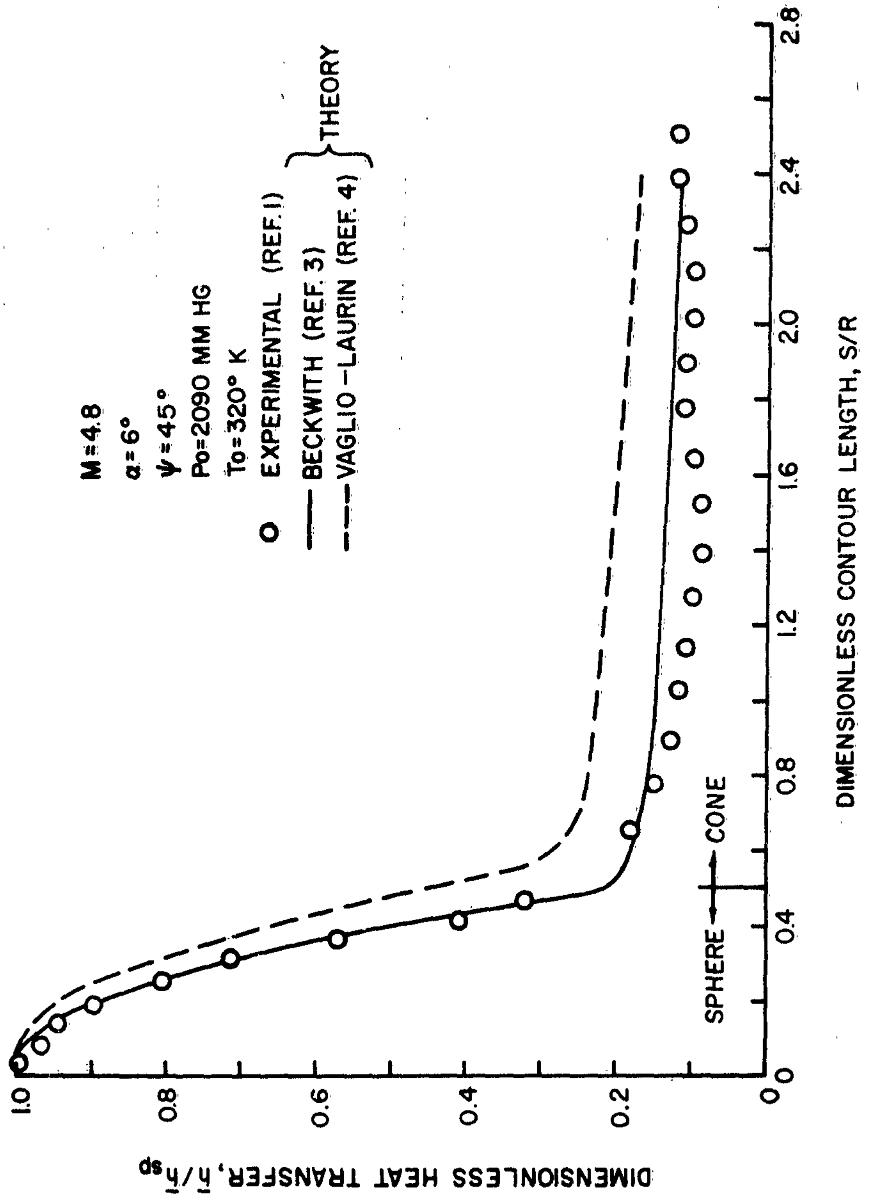

M=4.8
α=6°
ψ=45°
Po=2090 MM HG
To=320° K
○ EXPERIMENTAL (REF. 1)
—— BECKWITH (REF. 3)
– – – VAGLIO-LAURIN (REF. 4)
THEORY
SPHERE
CONE
DIMENSIONLESS HEAT TRANSFER, h/h_sp
DIMENSIONLESS CONTOUR LENGTH, S/R
0
0.2
0.4
0.6
0.8
1.0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8

FIGURE 6(b)

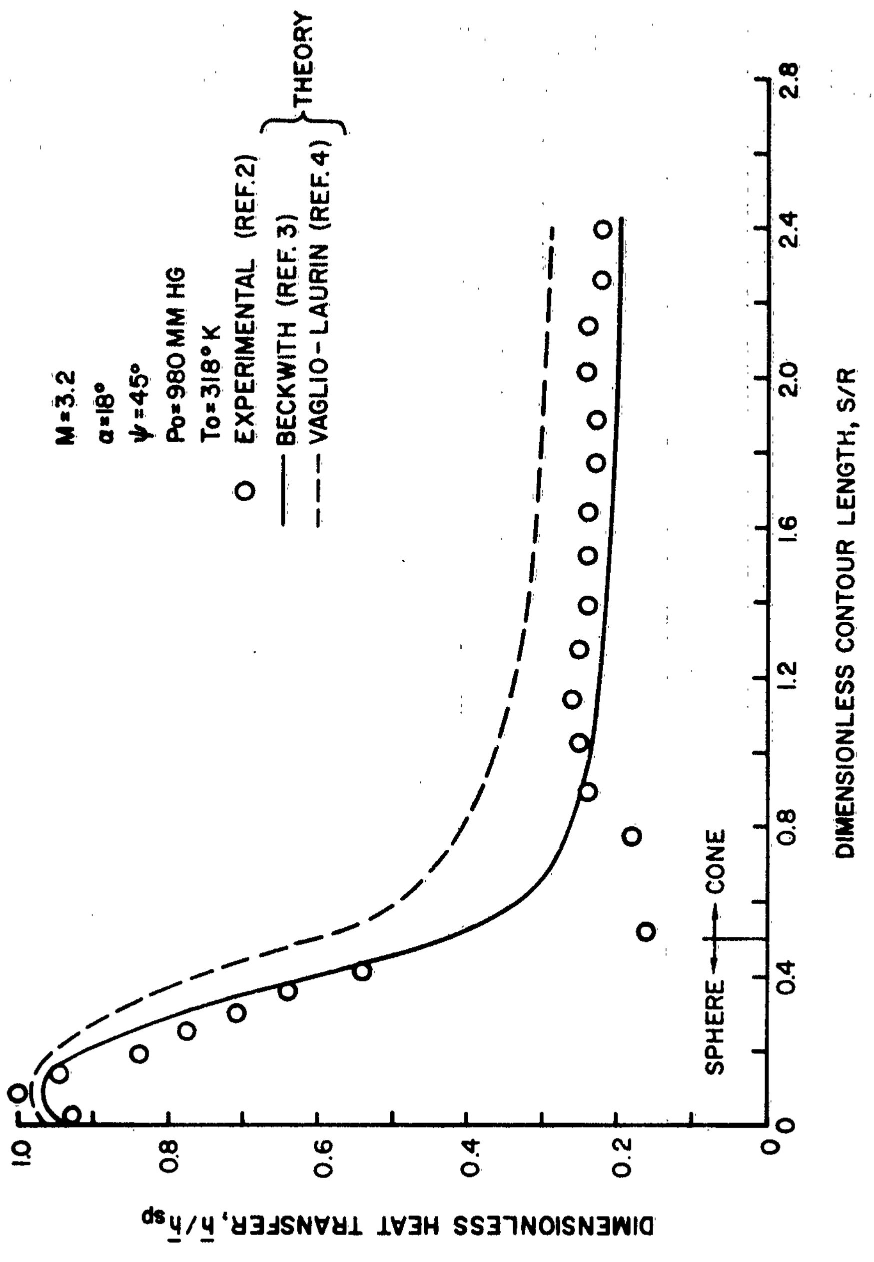


FIGURE 7(a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS S/R AT $\alpha=18°$, $\psi=45°$

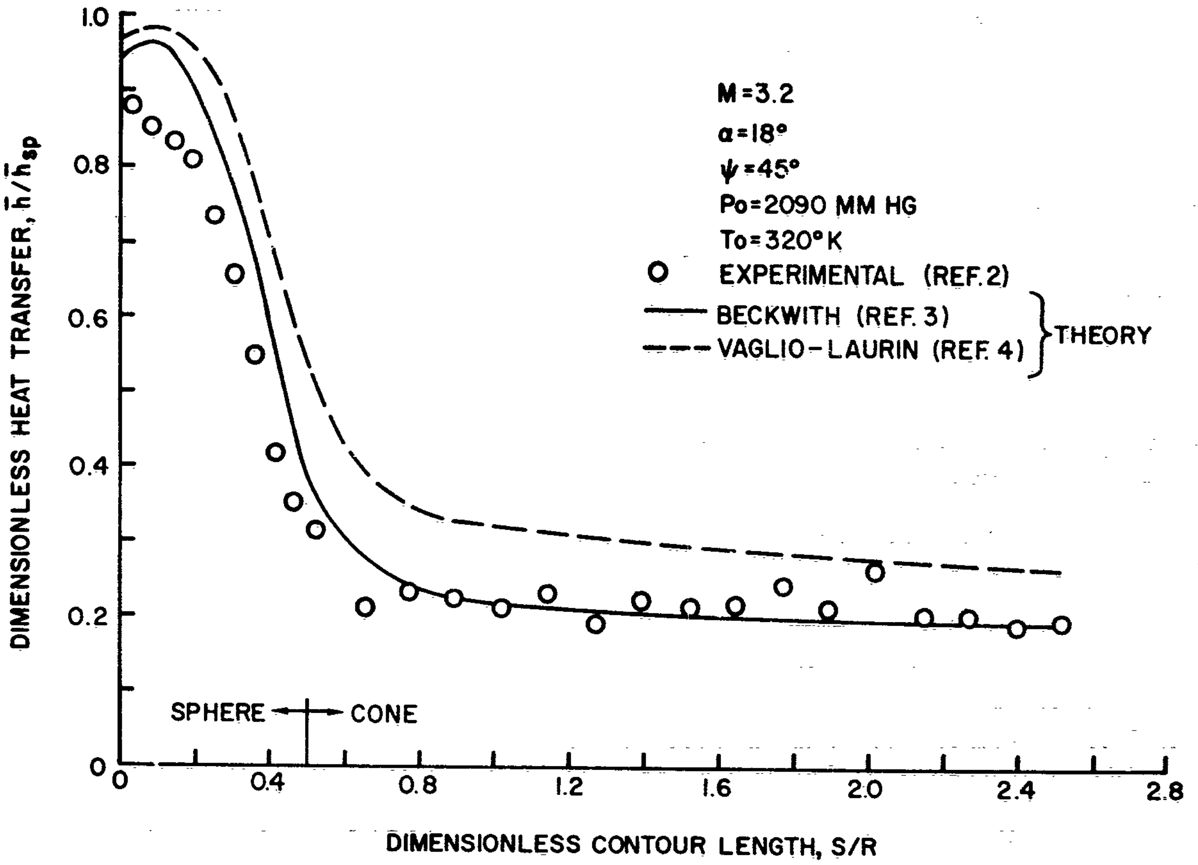

M=3.2
α=18°
ψ=45°
Po=2090 MM HG
To=320°K
EXPERIMENTAL (REF. 2)
BECKWITH (REF. 3)
VAGLIO-LAURIN (REF. 4)
THEORY
SPHERE
CONE
DIMENSIONLESS HEAT TRANSFER, $\bar{h}/\bar{h}_{sp}$
DIMENSIONLESS CONTOUR LENGTH, S/R
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8

FIGURE 7(b)

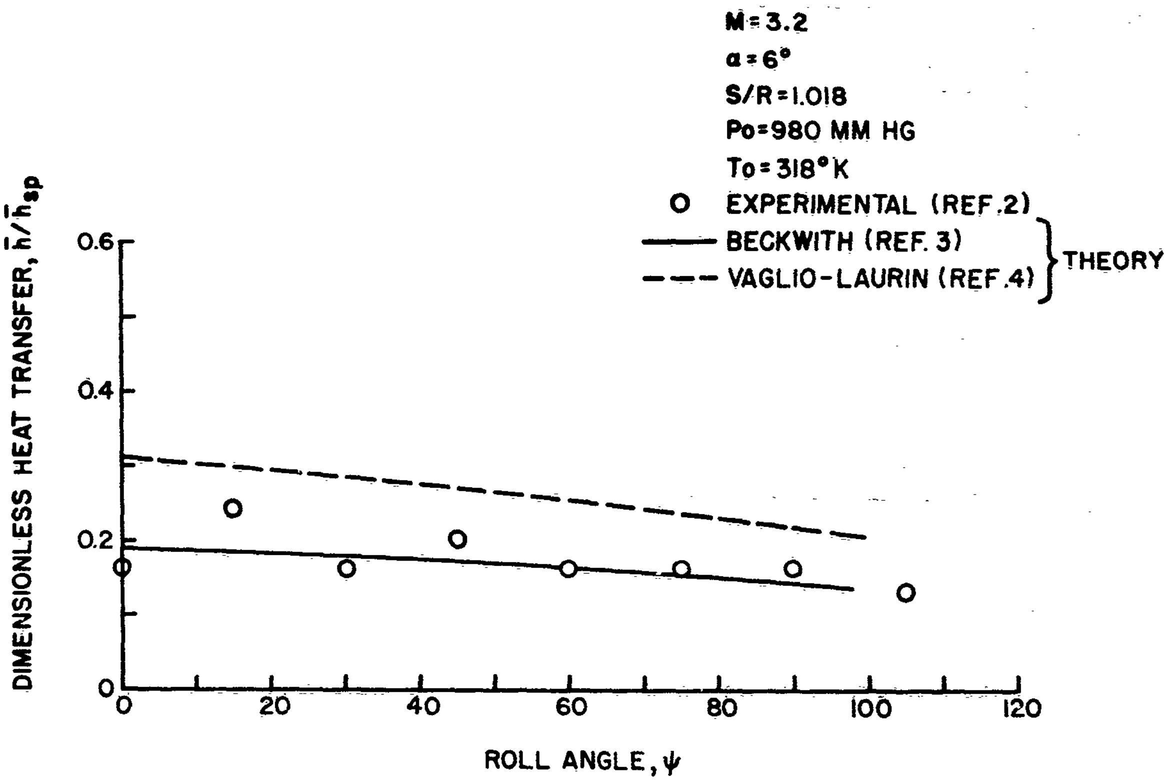


FIGURE 8(a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS ψ AT α = 6°, S/R = 1.018

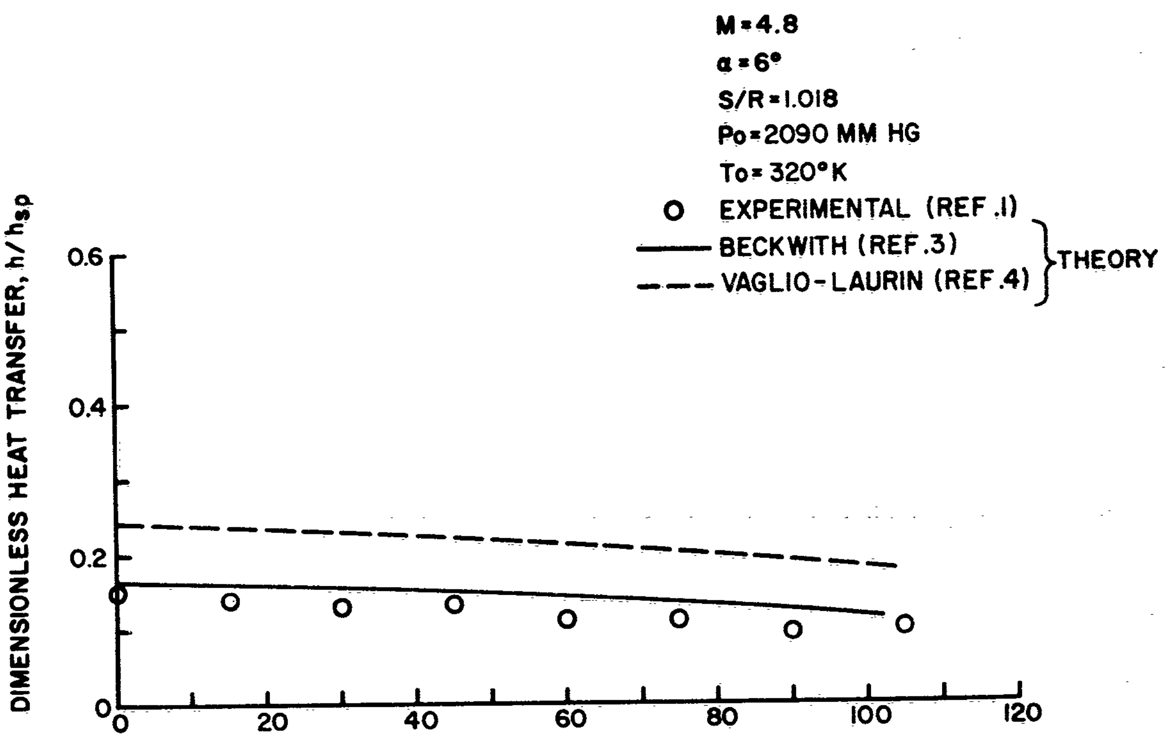

M = 4.8
α = 6°
S/R = 1.018
Po = 2090 MM HG
To = 320°K
○ EXPERIMENTAL (REF. 1)
BECKWITH (REF. 3)
VAGLIO-LAURIN (REF. 4)
THEORY
DIMENSIONLESS HEAT TRANSFER, $\bar{h}/\bar{h}_{sp}$
0.6
0.4
0.2
0
0
20
40
60
80
100
120
ROLL ANGLE, ψ

FIGURE 8 (b)

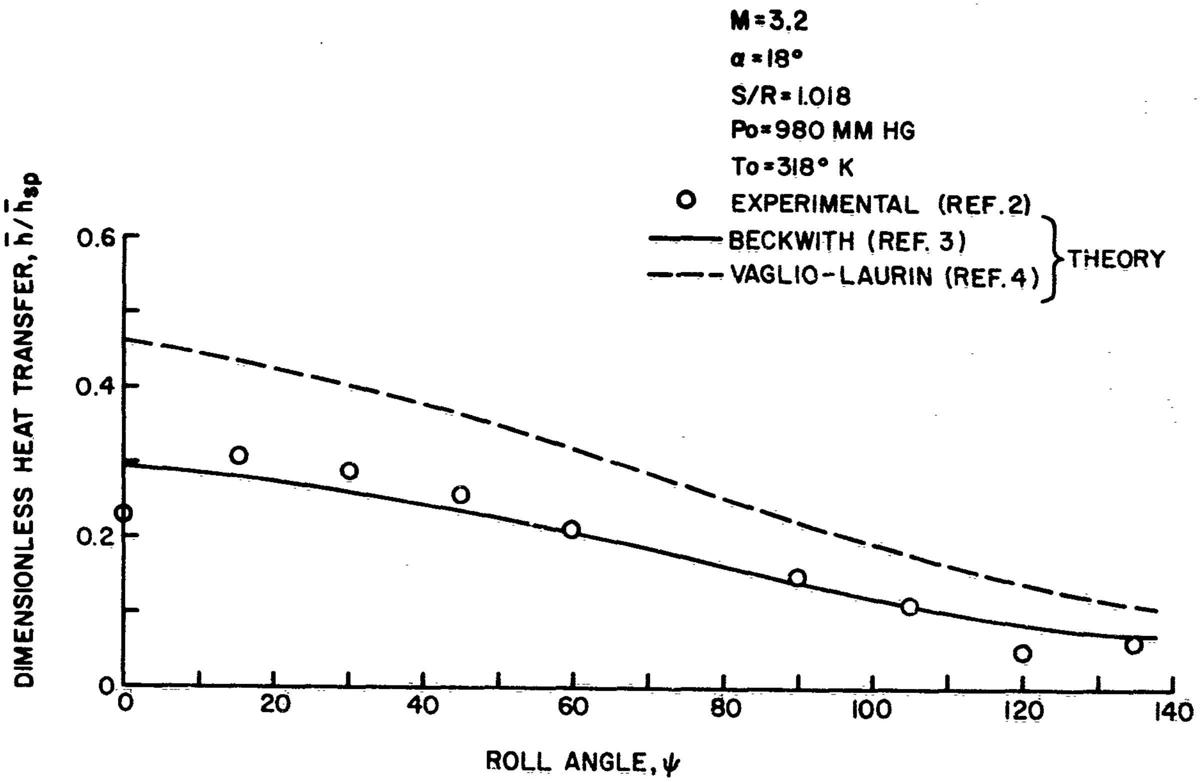


FIGURE 9 (a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS ψ AT $\alpha = 18°$ S/R = 1.018

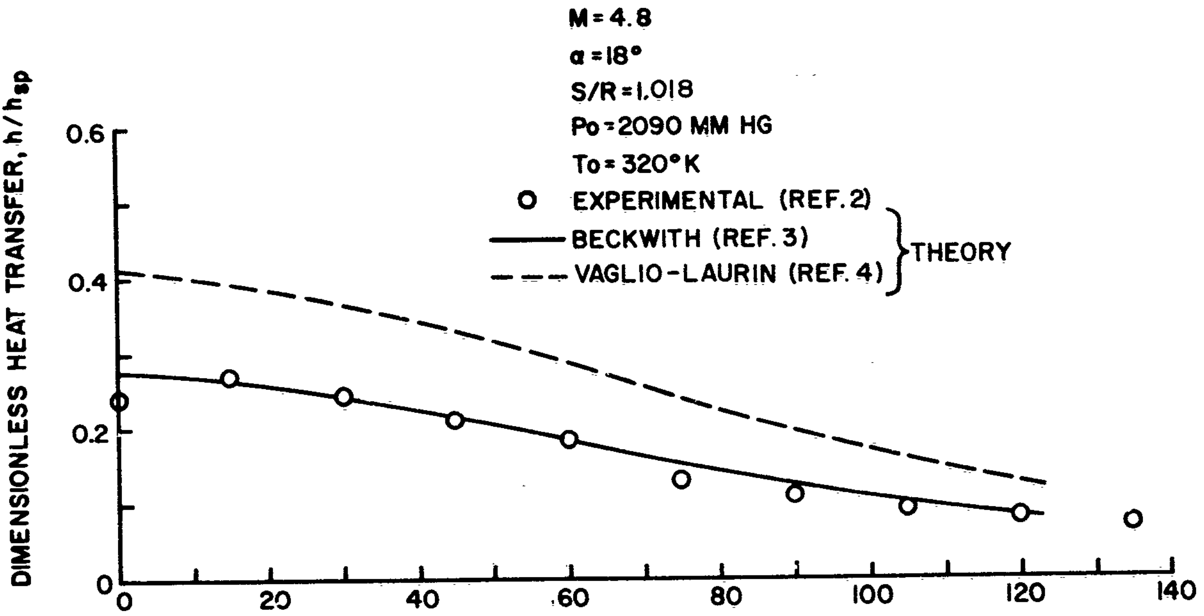

M = 4.8
α = 18°
S/R = 1.018
Po = 2090 MM HG
To = 320°K
○ EXPERIMENTAL (REF. 2)
BECKWITH (REF. 3)
VAGLIO-LAURIN (REF. 4)
THEORY
DIMENSIONLESS HEAT TRANSFER, h̄/h̄sp
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
ROLL ANGLE, ψ

FIGURE 9(b)

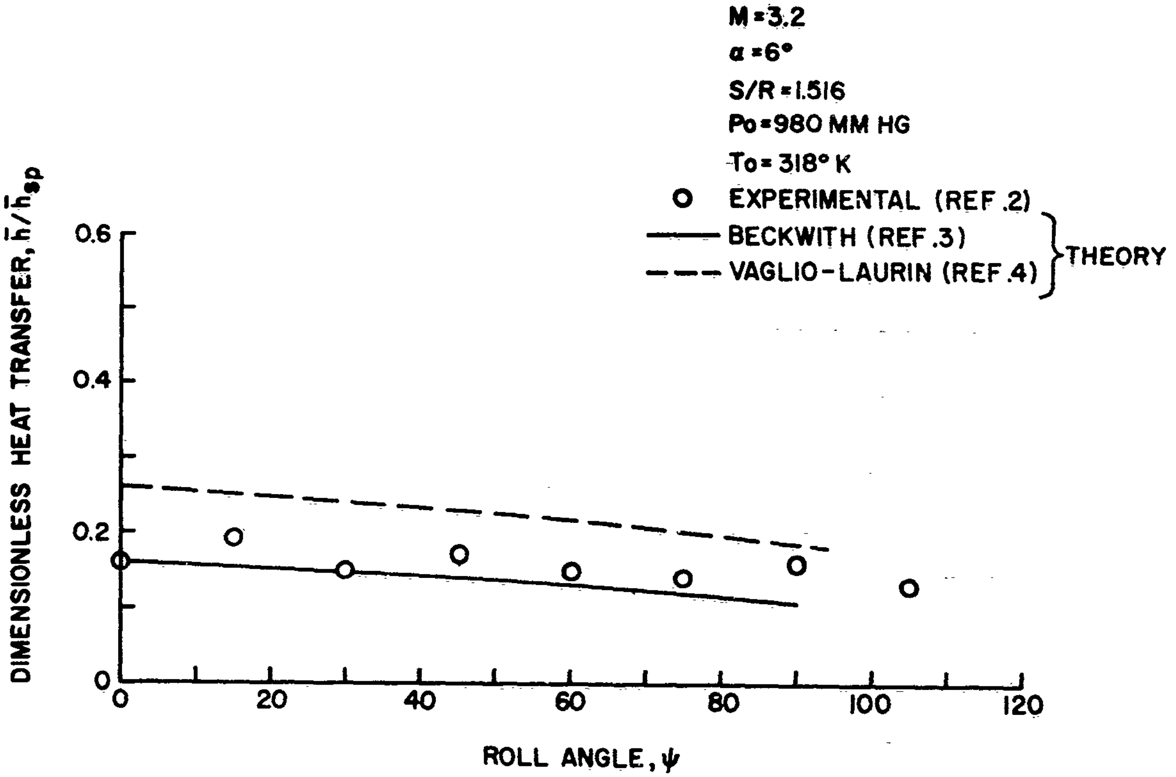


FIGURE 10 (a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTIAL HEAT TRANSFER VERSUS ψ AT $\alpha = 6°$, S/R = 1.516

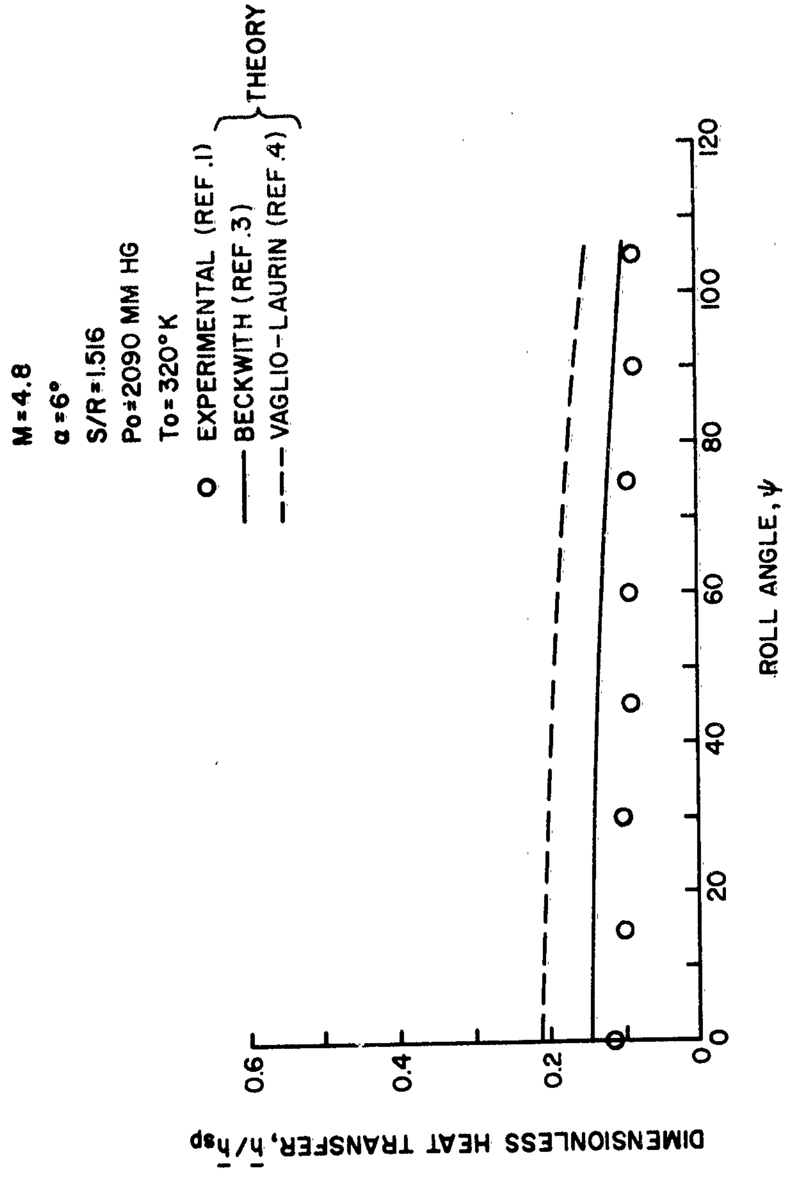

M=4.8
α=6°
S/R=1.516
Po=2090 MM HG
To=320°K
○ EXPERIMENTAL (REF. 1)
— BECKWITH (REF. 3)
--- VAGLIO-LAURIN (REF. 4)
THEORY
DIMENSIONLESS HEAT TRANSFER, $\bar{h}/\bar{h}_{sp}$
0
0.2
0.4
0.6
0
20
40
60
80
100
120
ROLL ANGLE, ψ

FIGURE 10 (b)

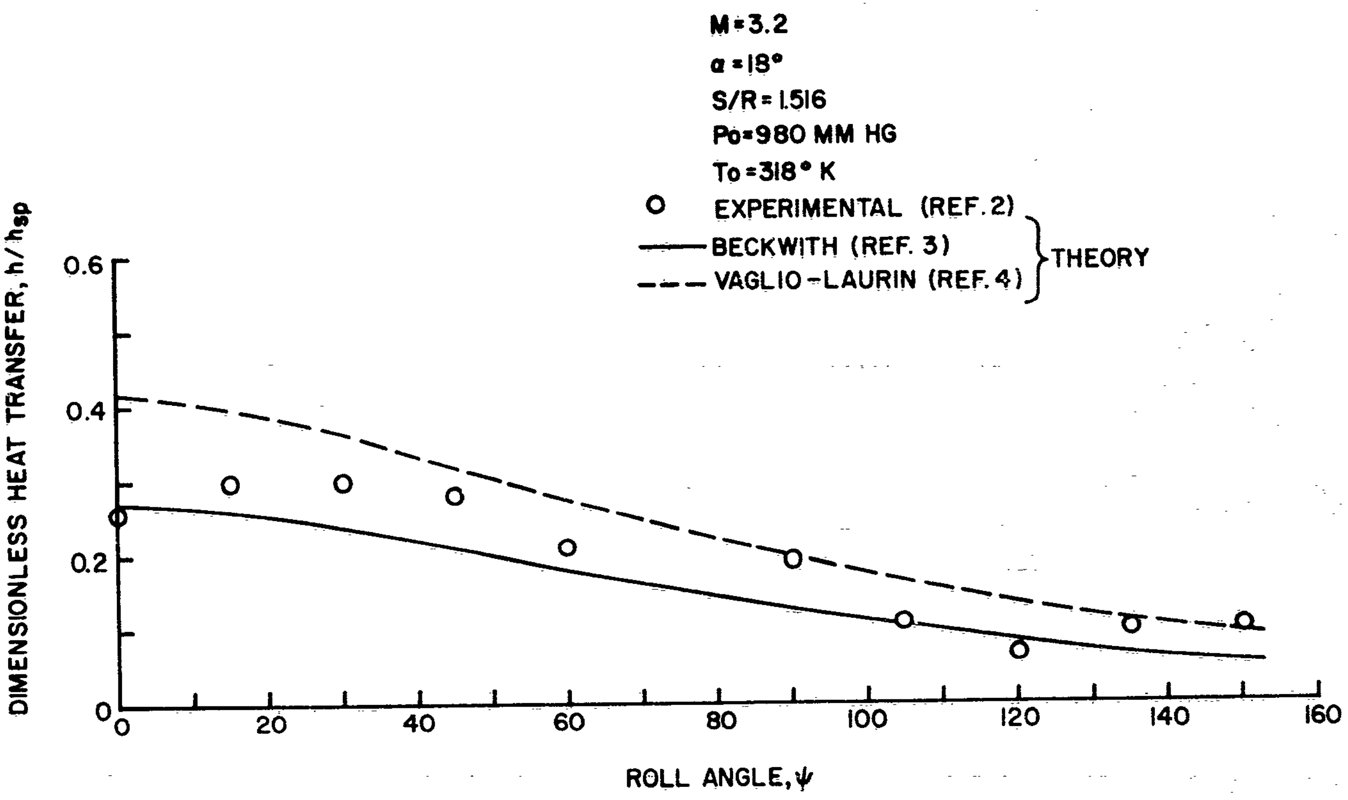


FIGURE 11 (a)-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VERSUS ψ AT $\alpha = 18°$; S/R=1.516

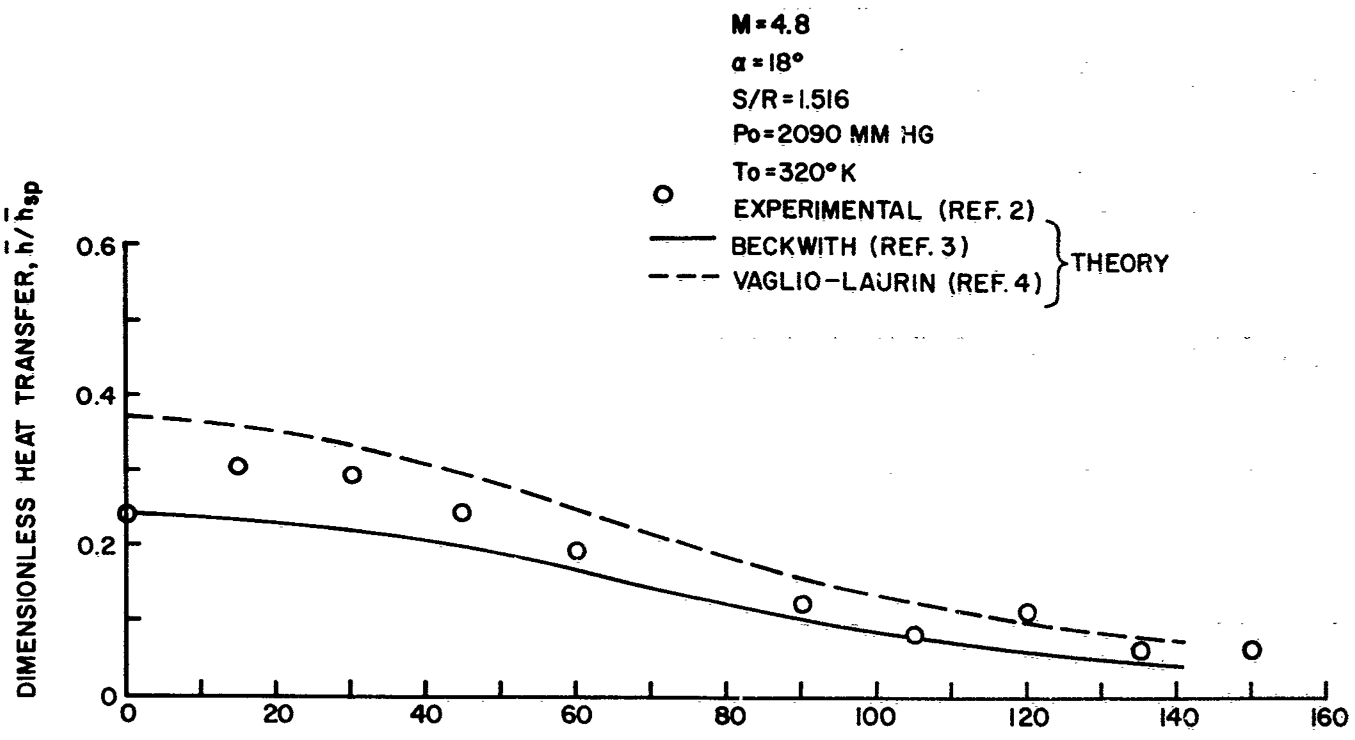

M = 4.8
α = 18°
S/R = 1.516
Po = 2090 MM HG
To = 320° K
EXPERIMENTAL (REF. 2)
BECKWITH (REF. 3)
VAGLIO-LAURIN (REF. 4)
THEORY
DIMENSIONLESS HEAT TRANSFER, $\bar{h}/\bar{h}_{sp}$
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
ROLL ANGLE, ψ

FIGURE 11 (b)

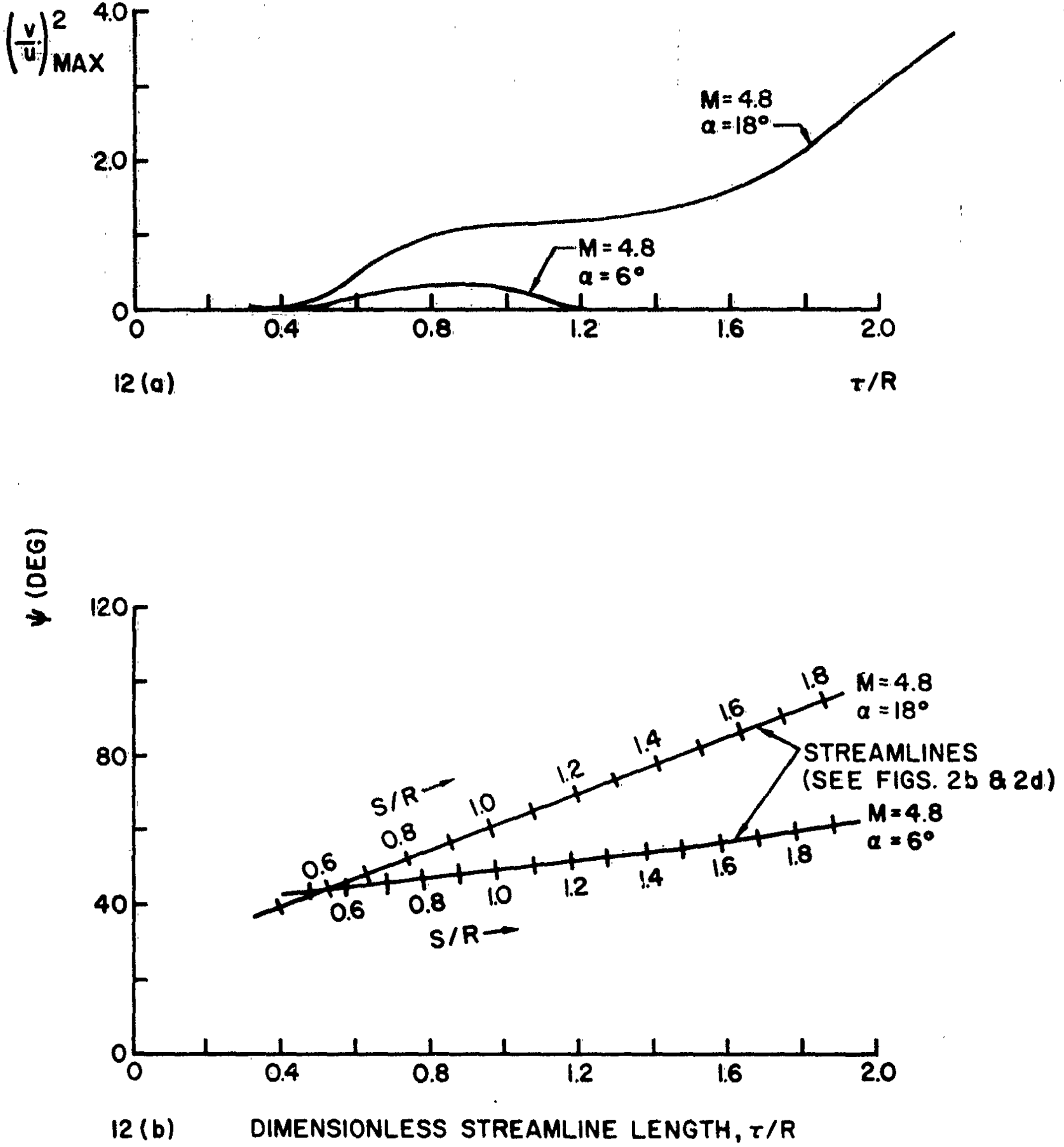


FIGURE 12 - THE MAXIMUM CROSS FLOW TO STREAMWISE VELOCITY RATIO ALONG TWO GIVEN STREAMLINES AT α = 6° AND α = 18°

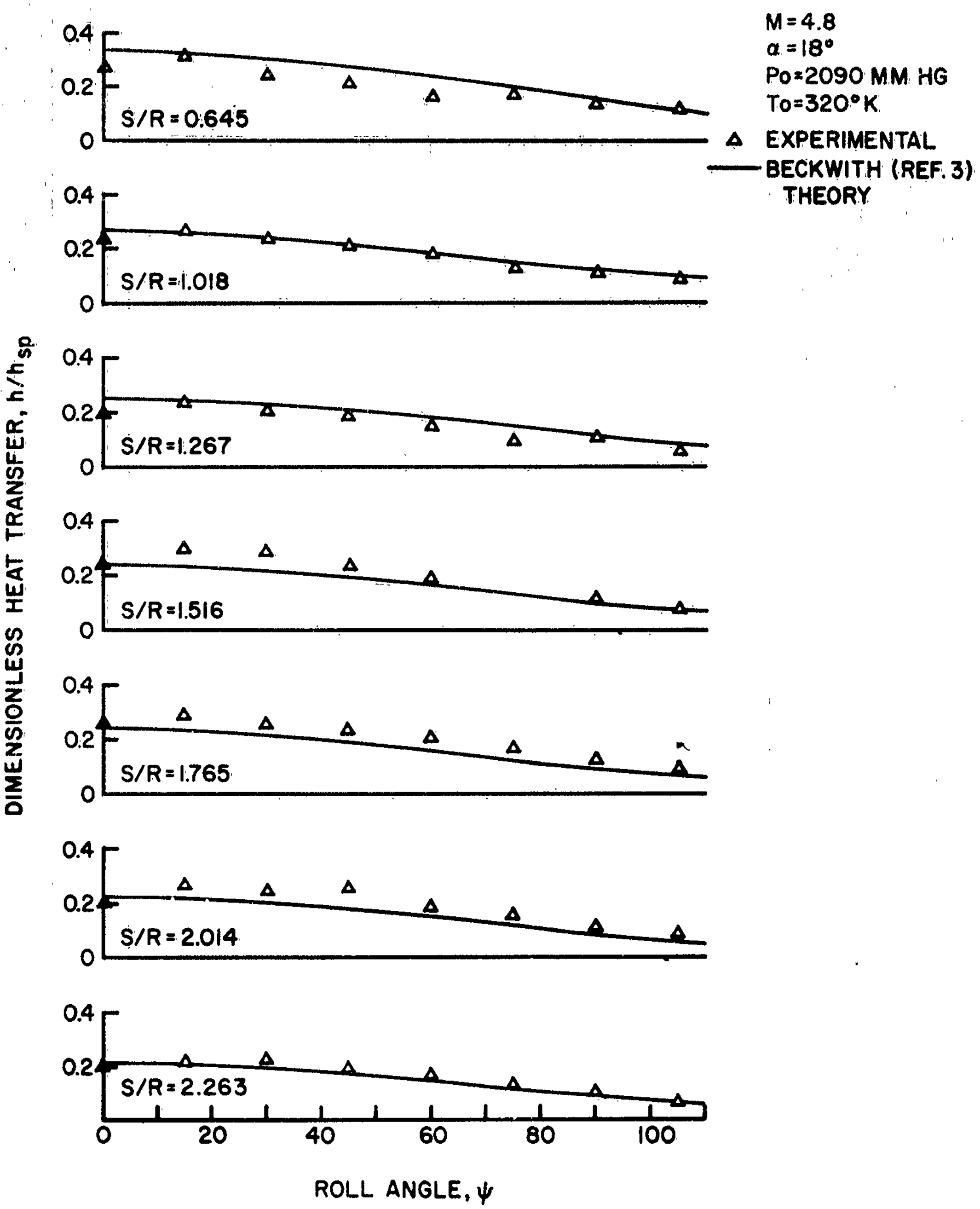


FIGURE 13-COMPARISON BETWEEN THE CALCULATED AND EXPERIMENTAL HEAT TRANSFER VS. ψ

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