NASA TECHNICAL NOTE

NASA TN D-2857

c. 1

NASA TN D-2857

THE RELATION BETWEEN SKIN FRICTION AND HEAT TRANSFER FOR THE COMPRESSIBLE TURBULENT BOUNDARY LAYER WITH GAS INJECTION

by C. C. Pappas and Arthur F. Okuno

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1965

NASA TN D-2857

THE RELATION BETWEEN SKIN FRICTION AND HEAT TRANSFER FOR THE COMPRESSIBLE TURBULENT BOUNDARY LAYER WITH GAS INJECTION

By C. C. Pappas and Arthur F. Okuno

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $2.00

THE RELATION BETWEEN SKIN FRICTION AND HEAT TRANSFER FOR THE COMPRESSIBLE TURBULENT BOUNDARY LAYER WITH GAS INJECTION

By C. C. Pappas and Arthur F. Okuno
Ames Research Center

SUMMARY

Average Stanton numbers and recovery factors of the turbulent boundary layer with gas injection of helium, air, and Freon-12 are presented for air flow over a sharp cone at cone Mach numbers of 0.7, 3.67, and 4.35 and Reynolds numbers near 2.5 million. The relative effectiveness of the injection gases in reducing the heat-transfer coefficient is as expected from theory and agrees with previously presented local measurements. The effect of Mach number on the reduction of Stanton number from its zero injection value is not nearly so great as the effect on the reduction in skin friction. For a Mach number of 0.7 the recovery factor for air and Freon injection generally decreases with increased injection and for helium injection the recovery factor rises to a maximum value of 1.25 and then decreases at higher rates of injection. For the supersonic Mach numbers the recovery factor initially decreases with injection of each gas and then rises to values that can exceed 1.0 at the highest injection rates.

The ratio of average Stanton number to one-half the skin-friction coefficient, designated here as Reynolds analogy factor, was determined over the range of experimental variables. For zero gas injection, the theoretical values of Reynolds analogy factor for flat-plate flow are 20 percent higher than experiment for subsonic flow over a cone. Similarly for supersonic flow, the theoretical flat-plate value is 20 percent higher than the measured value on a sharp cone at a cone Mach number near 4. Bradfield's local value for zero injection for cone flow at Mach number 3.7 is about 6.5 percent above the present Reynolds analogy factor results for supersonic flow.

For subsonic flow, the initial trends in the values of the Reynolds analogy factor of the theory and experiment are parallel with helium injection and also with air injection. With Freon injection the experimental Reynolds analogy factor is constant but the theoretical values increase linearly with injection.

For supersonic flow, with air injection, the theoretical values of Reynolds analogy factor increase linearly with injection and the experimental values generally decrease with injection. With helium injection, Reynolds analogy factor increases initially to a maximum value near 1.35 and then drops off to values near 0.55 at the high injection rates. With Freon injection there is the least variation in Reynolds analogy factor of the injection gases tested, the values generally decrease from a value of 1.1 to a value near 0.77 at the high rates of injection.

INTRODUCTION

The study of turbulent boundary layers with surface mass addition is of continuing interest. Slender entry bodies maintain high speeds through to the lower altitudes of the atmosphere with consequent development of turbulent boundary layers along the ablating surfaces. Similarly, intercept missiles also attain high speeds at low altitudes and develop turbulent boundary layers with the attendant high surface heating and skin friction. Therefore, a knowledge of the heating and skin-friction characteristics of the turbulent boundary layer with surface mass addition is essential for any mission analysis involving slender entry or intercept missiles.

Some theories treat the problem of surface mass injection into the turbulent boundary layer, but they require experimental substantiation at certain test conditions in order to allow extrapolation to other mission environments. Most of the numerous heat-transfer and skin-friction measurements were performed over limited ranges in Reynolds number, Mach number, and wall temperature ratio and the types of injection gases were restricted. Also, the test models were small and it was difficult to define the effective Reynolds number of the boundary layer. A systematic comparison of theory and experiment has proved to be difficult because of the varied experimental source material. This report presents average heat-transfer coefficients and recovery factors obtained on a sharp 15° porous cone with uniform surface injection of the gases, helium, air, and Freon-12. The Mach number range was from subsonic to near 5. The effect of Mach number on the reduction in average Stanton number from its zero injection value is shown as a function of the injection rate of each gas. The average skin-friction coefficients of reference 1 were converted to the test conditions corresponding to the heat-transfer data. Finally, the relation between average heat-transfer and skin-friction coefficients is systematically compared with theory in the form of a Reynolds analogy factor, $2C_H/C_F$, for the Mach number range $0 < M < 5$ for each injection gas.

NOTATION

A external area of porous surface of cone

A_1 area used to define average heat-transfer coefficients on cone

c_f local skin-friction coefficient

c_h local Stanton number

c_p specific heat

C_F average skin-friction coefficient

C_H average Stanton number

F injection mass flow normal to surface; $(\rho_w v_w)/(\rho_c u_c)$ for supersonic flow, $(\rho_w v_w)/(\rho_\infty u_\infty)$ for subsonic flow h heat-transfer coefficient defined in equation, $q = h(T_r - \overline{T}_w)$

M Mach number

M_c cone Mach number; value at cone surface for inviscid supersonic flow, free-stream value for subsonic flow

Pr* Prandtl number, $\mu c_p/k$, evaluated at temperature T^*

q heat-transfer rate to the wall

r temperature recovery factor, $(T_r - T_c)/(T_t - T_c)$

R_c Reynolds number for cone; $(u_c \rho_c s)/\mu_c$ for supersonic flow, $(u_\infty \rho_\infty s)/\mu_\infty$ for subsonic flow

R_x Reynolds number based on distance along plate and free-stream properties, $(u_\infty \rho_\infty x)/\mu_\infty$

s effective length of boundary-layer run along the cone

T temperature

T* reference temperature, $T^* = T_c + 0.5(T_w - T_c) + 0.22(T_{ro} - T_c)$

u velocity component parallel to cone surface or in stream direction

v velocity component normal to cone surface

x distance along flat plate from leading edge

μ viscosity of gas

ρ density of gas

Subscripts

c cone condition; cone surface value for inviscid supersonic flow, free-stream value for subsonic flow

g value for internal coolant

o zero injection condition

r adiabatic or recovery condition

t stagnation condition of stream

w cone surface condition

∞ free-stream condition

PRESENTATION OF DATA AND DISCUSSION

One of the purposes of this report is to present a comparison of average heat-transfer and skin-friction coefficients with surface gas injection in the form of Reynolds analogy factor, $2C_H/C_F$, and to measure the result with respect to theoretical predictions. An optimum comparison requires that both skin-friction and heat-transfer measurements be made on the same model in the same flow environment, and with the same surface distribution of gas injection and effective boundary-layer Reynolds numbers. It is difficult to incorporate two types of instrumentation into one test model; consequently, two similar test models are usually required. Therefore, the two primary sources of experimental material, references 1 and 2, have been utilized to obtain the average skin-friction and average heat-transfer coefficients. Both tests used 15° total included angle sharp cones, a fairly uniform surface porosity distribution, nearly equivalent flow Reynolds numbers, and a free-stream Mach number range from 0.7 to 4.8. The injection gases in both cases were helium, air, and Freon-12 (CCl_2F_2) with a molecular weight range from 4 to 120.9. In both tests the boundary layer was made turbulent with garnet paper trips on the nonporous tip area of the cones.

Effective Reynolds Numbers of the Tripped Turbulent Boundary Layer

In the representation of the local Stanton number in reference 2, the effective Reynolds number was based on a length of boundary-layer run as a distance from near the start of the porous surface. The effective origin of the boundary layer with injection was located using shadowgraph pictures of the region where the boundary layer is rapidly thickening and extrapolating the boundary-layer thickness to the zero value. The reason for selecting this effective length of the boundary layer (stated on pp. 13-14 of ref. 2) is that all the heat-transfer measurements were obtained with gas injection and the zero injection Stanton number values were extrapolated values. The same definition of the effective Reynolds number (as in ref. 2) is used in the present report to represent the average Stanton numbers of the turbulent boundary layer.

In the representation of the total skin-friction coefficients in reference 1 the length of the cone ray was used in the definition of the effective Reynolds number of the turbulent boundary layer and this definition is retained in the present report. Some explanation is required to account for the difference in definition of the effective boundary-layer length. For all cases, with or without injection, the measured skin-friction drag is for the whole wetted area of the cone including all the nonporous forward area where the trip is located. With zero injection the effect of the trip is to thicken the boundary layer and move the effective origin of the boundary layer toward the apex of the cone in the region of diminishing surface area; therefore the total length of the cone ray is a good choice for the effective length of run of the boundary layer. With injection the effective origin of the boundary layer moves close to the start of the porous surface, but the skin-friction force as presented in reference 1 always included the skin-friction drag of the nonporous forward region of the cone. Two approaches were possible with surface injection; one was to estimate the skin-friction drag of the nonporous region, subtract this from the values reported in reference 1, and correlate this skin-friction coefficient using a Reynolds number based on a length from the start of the porous region. The second approach was to adopt the method of reference 1 where, with injection, this same skin friction of nonporous area is included in the reported values of skin friction and the effective boundary-layer length is defined from the cone apex. Both methods without injection use the same skin-friction correlation with respect to Reynolds number but the method adopted gives skin-friction coefficient ratios C_F/C_{F_o} which decrease less with injection because of the lower zero injection value and a constant drag contribution of the trip region. The adopted method, (that of ref. 1) therefore, gives a more conservative reduction in skin friction with injection from the zero injection value. An example of the difference in reduction of skin friction for maximum helium injection rates of table I, reference 1, for M_c values 0.7, 3.21, and 4.30 is as follows: The values of C_F/C_{F_o} ratio from method of reference 1 are, respectively, 0.519, 0.199, and 0.240 as compared to 0.468, 0.158, and 0.197 for the other method. The differences are 5.1, 4.1, and 4.3 percent of the zero injection values.

Average Skin-Friction Coefficients

Average skin-friction coefficients were obtained on a 15° cone with and without surface mass injection. The test cone is shown in figure 1. The total axial-skin-friction force on the cone was equal to the resultant of the external pressure force, the base pressure force, the strain-gage flexure force, and the measured injection force exerted by the flexible gas supply tubing. The average skin-friction coefficients of reference 1, supplemented by the low Mach number local measurements for air injection of reference 3, are presented in figures 2(a), 2(b), and 2(c). The ratio of skin friction with injection to that without injection is plotted as a function of Mach number for fixed values of the injection rate parameter $2F/C_{F_o}$ (or $2F/c_{f_o}$). A necessary accompaniment of these data are the measurements of the average skin-friction coefficient as a function of Reynolds number at each Mach number considered; these values are presented in figure 3 for the sharp cone. With these skin-friction data, the actual skin-friction coefficient corresponding to the Mach number, Reynolds number, and gas injection rate of the heat-transfer measurements was obtained, thus allowing calculation of Reynolds analogy factor for the turbulent boundary layer on a 15° sharp cone.

Average Stanton Numbers

The cone model which was instrumented for heat-transfer measurements is shown in figure 4. The local heat-transfer measurements obtained at the first seven thermocouples of ray A of the cone, and presented in reference 2, have been integrated to obtain the average heat-transfer values for this report by the equation

$$q = \frac{1}{A_1}\int_0^{A_1}(\rho v)_w c_{p_g}(T_w - T_g)dA$$

The average injection rate and the average wall temperature were calculated by the equations

$$F = \frac{1}{A_1}\int_0^{A_1}\frac{(\rho v)_w}{\rho_c u_c}\,dA$$

and

$$\bar{T}_w = \frac{1}{A_1}\int_0^{A_1} T_w\,dA$$

These integrals were evaluated numerically at each wall temperature level for each injection rate. A plot of q/T_t as a function of T_w/T_t was sufficient to define the heat-transfer coefficient, h, and the recovery temperature, T_r, using the linear relation $q = h(T_r - \bar{T}_w)$ where h = constant for $\bar{T}_w$ near T_r. The Stanton number, $C_H = h/(\rho u c_p)_c$, with air injection was plotted as a function of the injection rate, and the values were extrapolated to zero injection to get the value C_{H_o}. The value of C_{H_o} obtained from the air data was considered the reference value with zero injection for all the injection gases. The Stanton number ratio values, C_H/C_{H_o}, (normalized with respect to the zero injection value) are plotted as a function of the normalized injection rate, F/C_{H_o}, in figures 5(a), 5(b), and 5(c) for the cone Mach numbers 0.7, 3.67, and 4.35 for the injection gases, helium, air, and Freon-12. Smooth curves were drawn through each set of heat-transfer data corresponding to the type of injection gas. The dashed portions of the faired curves are extrapolations or interpolations into less well-defined areas of measurements. The average heat-transfer coefficient ratio, C_H/C_{H_o}, at $M_c = 0.7$ and for all injection gases generally drops off slightly less rapidly with injection rate F/C_{H_o} than the local values of c_h/c_{h_o} with injection F/c_{h_o}. For all injection gases at Mach numbers 3.67 and 4.35, the variation of the average coefficient C_H/C_{H_o} with injection is in general agreement with the variation of the local values c_h/c_{h_o}; compare with figures 7(a) to 7(f) and 8(a) to 8(f) of reference 2. Agreement between the variation of the local and average coefficients with injection was to be expected since for all test Mach numbers the c_h/c_{h_o} variation with F/c_{h_o} was found to be generally independent of Reynolds number (or distance location along the cone).

The heat-transfer coefficients at the two highest rates of helium injection are included in figure 5(c) to emphasize the difference between the heat-transfer rate to the wall and the heat-transfer coefficient, as normally defined, at these high injection rates. The heat transfer to the wall was constant and independent of wall temperature for the two highest injection conditions and, in fact, was higher for the highest injection rate. The recovery temperature value could not, of course, be obtained under these conditions.

Average Recovery Factors

The average recovery factor with gas injection defined over the porous area A_1 is presented in figures 6(a), 6(b), and 6(c) for the cone Mach numbers 0.7, 3.67, and 4.35, respectively. Each experimental value of recovery factor corresponds to a value of Stanton number ratio C_H/C_{H_O} of the previous figure. The trend in values of the average recovery factor, as indicated by the faired curves, follows that of the local values, discussed in some detail in reference 2. The variation of the recovery factor with helium injection rate for the Mach number 0.7 tests, which may seem unusual and is noted in reference 2, has some precedent. Tewfik, Eckert, and Shirtliffe (ref. 4) have measured in a low-speed air stream an increase in recovery temperature up to their maximum helium injection rate near $F = 0.001$ (which would correspond to F/C_{H_O} values of 0.4 in fig. 6(a)); this is in agreement with the present trend except that for injection rates higher than $F/C_{H_O} = 0.4$ a reduction from the maximum recovery factor is noted. With air and Freon-12 injection the recovery factor generally decreases with increased injection.

For the cone Mach numbers 3.67 and 4.35 the value of recovery factor for each injection gas decreases initially with injection and then rises to values near to and larger than the zero injection value. For high rates of injection of helium (and of Freon, at $M_c = 4.35$) the recovery temperature exceeded the total stream temperature (or $r = 1.0$). To the authors' knowledge, this increase in recovery factor at the high injection rates has not been measured by other experimenters. The trend to high values of recovery factor indicates that the heat-transfer rate to the wall will not vary much with change in wall temperature level for finite heat-transfer rates.

Effects of Mach Number on Reduction of Stanton Number With Injection

The effect of Mach number on the reduction in average heat-transfer coefficient with gas injection is conveniently shown in figures 7(a), 7(b), and 7(c) by plotting C_H/C_{H_O} as a function of Mach number at constant values of the injection rate parameter F/C_{H_O}. With air injection, the effect of Mach number on the reduction of heat transfer is small; there is a slight decrease in the reduction of heat-transfer coefficient with increase in Mach number. With helium injection, there is generally a decreased effectiveness in reducing the Stanton number from its zero injection value with increasing Mach number. Note that the dashed symbols in figure 7 correspond to the values of the dashed curves in figure 5. For the low injection rate value near $F/C_{H_O} = 0.1$, the Stanton number is greater than the zero injection value at the two high Mach numbers 3.67 and 4.35. With Freon injection the effect of Mach number is very small on the reduction in Stanton number from the zero injection value.

A comparison with figures 2(a), 2(b), and 2(c) indicates that there is less effect of Mach number on the reduction in average Stanton number than on the reduction in the average skin-friction coefficient. This trend of average Stanton number ratio with Mach number could be inferred from the local heat-transfer measurements of reference 2, although the exact magnitude of the trend required the integration of the local variations.

Rubesin's theory (ref. 5) predicts the magnitude of reduction of the local heat-transfer coefficient with air injection and the trend with Mach number quite well (see fig. 17, ref. 2). The comparison of the average heat-transfer coefficient with Rubesin's theory for air injection is made in figure 8 over the Mach number range from 0 to 4, but here the theoretical values at Mach number 4 are somewhat higher than the experimental values. This result was to be expected because the experimental local values of c_h/c_{h_o} did not vary appreciably with Reynolds number when plotted as a function of F/c_{h_o}; however, the theoretical average values (with injection) up to $R_x = 10^6$ (for $M = 4$, $T_w = T_t$) are higher relative to the theoretical zero injection value (see fig. 8(e), ref. 5).

Relation Between Stanton Number and Skin-Friction Coefficient With Gas Injection

A comparison of the skin-friction and heat-transfer coefficients is made in the final figures 9(a), 9(b), and 9(c) in the form of Reynolds analogy factor $2C_H/C_F$ as a function of the average injection rate F. For air injection, figure 9(a), the experimental values of $2C_H/C_F$ obtained for a sharp cone are compared with the flat-plate theory of Rubesin over nearly the same Mach number range. At zero injection the theoretical value exceeds experiment by nearly 20 percent for the low and high Mach numbers. Very little additional data is available for judging whether the 20-percent difference is a result of comparing cone flow to flat plate flow or whether it is a particular result of the experimental techniques. Bradfield (ref. 6) measured on a 15° cone both local heat transfer and skin friction at $M_c = 3.7$ for zero gas injection. The mean value of the local Reynolds analogy factor obtained from figure 7 of that report is $2c_h/c_f = 0.90\ (1.265) = 1.14$ which is about 6.5 percent greater than the present result for $M_c = 3.67$ and 2.7 percent greater than the $M_c = 4.35$ result. Bradfield concludes from figures 7 and 8 of his report that $2c_h/c_f = Pr^{*-2/3} \approx 1.265$ for $M_c = 3.7$ represents the cone data; however, this result would be based on only two of ten experimental heat-transfer measurements shown in figure 7.

The comparison of the Reynolds analogy factor of the cone results with flat-plate theory for <u>air injection</u> indicates that for subsonic flow the trends with increased injection F are very similar although the theoretical values are about 20 percent greater than experiment for injection values up to $F = 0.003$. For the two higher Mach numbers, the trend of the experimental values $2C_H/C_F$ generally decreases with increased injection rate, whereas the theoretical values increase linearly with increased injection. At the highest injection rate $F \approx 0.003$ the experimental value is about 50 percent of the theoretical value for $M_c = 4.0$.

With helium injection, the comparison of experimental values for subsonic flow can be made with the flat-plate theory of Rubesin and Pappas (ref. 7). Again, for subsonic flow, the initial trend with increased injection of the experimental and theoretical values is the same, but for injection rates $F > 0.0007$ the trend changes and the values tend to diverge. For the two highest Mach numbers, the experimental value of $2C_H/C_F$ increases very rapidly initially to a maximum value of 1.36 and then drops off to a value near 0.6 at injection rates of 0.0012. The trend in Reynolds analogy factor for Mach number near 4 is certainly much different than for the subsonic flow over the sharp cone. The considerable variation of the experimental value of Reynolds analogy factor with injection rate of helium - and for air - should caution against the common use of the Reynolds analogy value of 1.0 for turbulent boundary layers - at least for cone flows.

With Freon-12 injection, a comparison with the subsonic theory of reference 7 can again be made. In this case the experimental values of $2C_H/C_F$ do not vary as predicted by the subsonic theory, the experimental values remain at $2C_H/C_F \approx 1$ independent of the injection rate. The theory indicates an initial value 20 percent above experiment and this value increases linearly with injection to a value of 1.46 at an injection rate $F = 0.0035$. At the higher Mach numbers, the experimental values at zero injection are near 1.1 and then generally decrease to a value near 0.77 at $F = 0.0035$.

Apparently then, the lighter the injection gas the greater is the variation in Reynolds analogy factor with injection and with Mach number from subsonic to supersonic flow. The flat-plate theories considered here do not adequately predict the behavior of the Reynolds analogy factor on a sharp cone with gas injection, and the experimental variation is sufficient to warrant an investigation where both skin friction and heat transfer can be measured on the same test model in an identical flow environment over the range of test variables.

CONCLUDING REMARKS

A systematic presentation and comparison of experimental average heat-transfer and skin-friction coefficients of the turbulent boundary layer has been made for air flow over 15° sharp cones with surface injection of the light gas helium, air, and heavy gas Freon-12. Some concluding statements may be made concerning this summary report.

The relative effectiveness of the injection gases in reducing the average heat-transfer coefficient was as expected from theory and in agreement with previously presented local measurements of reference 2.

The effect of Mach number in the range from subsonic to $M = 4.8$, on the reduction in average Stanton number ratio C_H/C_{H_O}, was not nearly so great as the effect on the reduction in average skin-friction coefficient ratio

C_F/C_{F_o}, but the general trend was that the relative reduction in heat-transfer coefficient decreased slightly with increasing Mach number at given injection rate F/C_{H_o}.

The experimental variation of Reynolds analogy factor with injection of the gases, helium, air, and Freon-12, obtained on a sharp cone is not adequately predicted by the flat-plate theories considered in this report. Also, the experimental value with injection can differ significantly from the commonly used value of 1.0.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., March 8, 1965

REFERENCES

1. Pappas, Constantine C.; and Okuno, Arthur F.: Measurements of Skin Friction of the Compressible Turbulent Boundary Layer on a Cone With Foreign Gas Injection. J. Aerospace Sci., vol. 27, no. 5, May 1960, pp. 321-333.

2. Pappas, C. C.; and Okuno, Arthur F.: Measurement of Heat Transfer and Recovery Factor of a Compressible Turbulent Boundary Layer on a Sharp Cone With Foreign Gas Injection. NASA TN D-2230, 1964.

3. Mickley, H. S.; and Davis, R. S.: Momentum Transfer for Flow Over a Flat Plate With Blowing. NACA TN 4017, 1957.

4. Tewfik, O. E.; Eckert, E. R. G.; and Shirtliffe, C. J.: Thermal Diffusion Effects on Energy Transfer in a Turbulent Boundary Layer With Helium Injection. Proceedings of the 1962 Heat Transfer and Fluid Mech. Inst., June 1962, pp. 42-61.

5. Rubesin, Morris W.: An Analytical Estimation of the Effect of Transpiration Cooling on the Heat-Transfer and Skin-Friction Characteristics of a Compressible, Turbulent Boundary Layer. NACA TN 3341, 1954.

6. Bradfield, W. S.: Conical Turbulent Boundary Layer Experiments and a Correlation With Flat Plate Data. Trans. ASME, vol. 82, pt. 2, ser. C, J. Heat Transfer, May 1960, pp. 94-100.

7. Rubesin, Morris W.; and Pappas, Constantine C.: An Analysis of the Turbulent Boundary Layer Characteristics on a Flat Plate With Distributed Light-Gas Injection. NACA TN 4149, 1958.

8. Sommer, Simon C.; and Short, Barbara J.: Free-Flight Measurements of Turbulent Boundary Layer Skin Friction in the Presence of Severe Aerodynamic Heating at Mach Numbers From 2.8 to 7.0. NACA TN 3391, 1955.

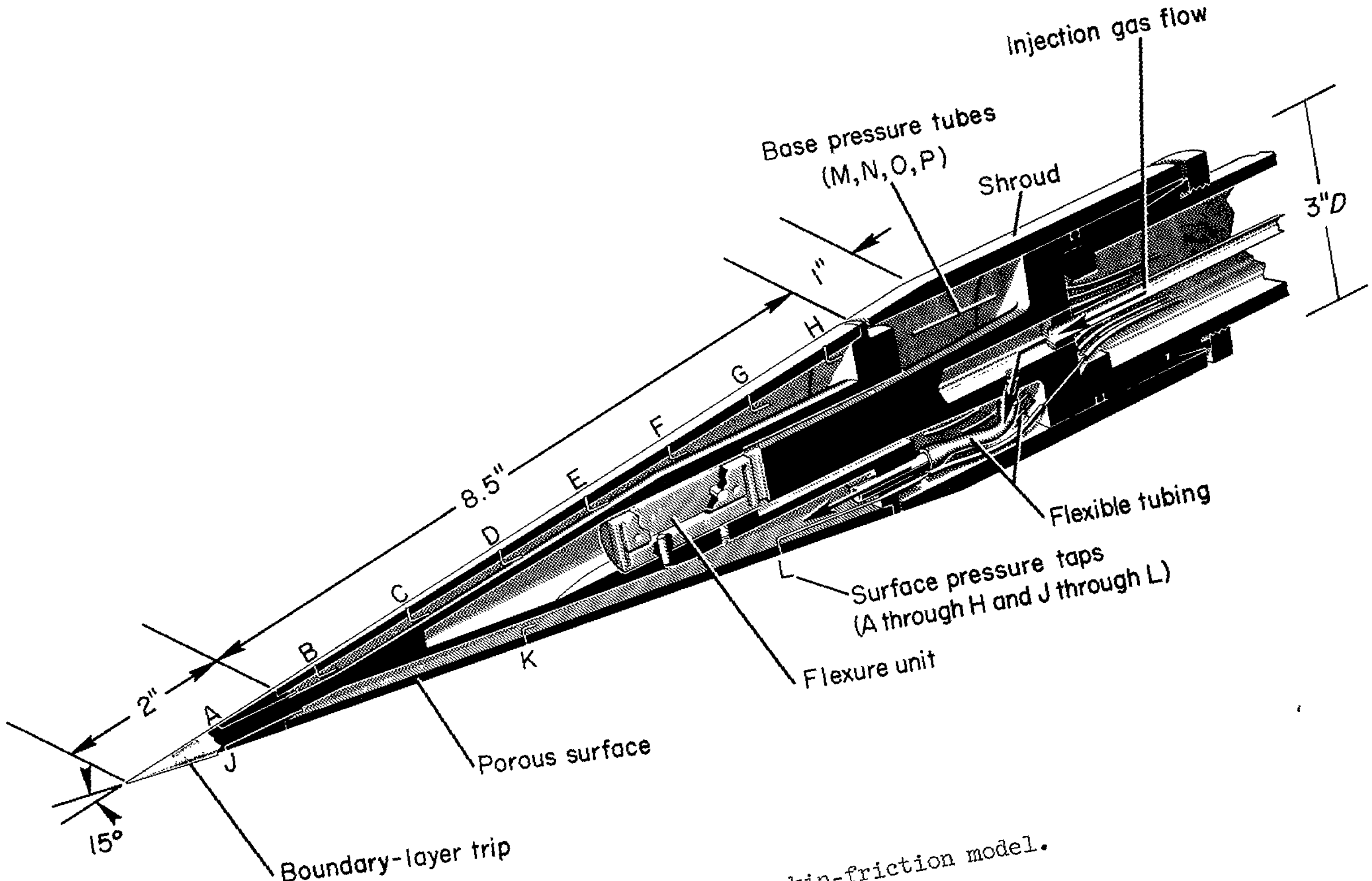
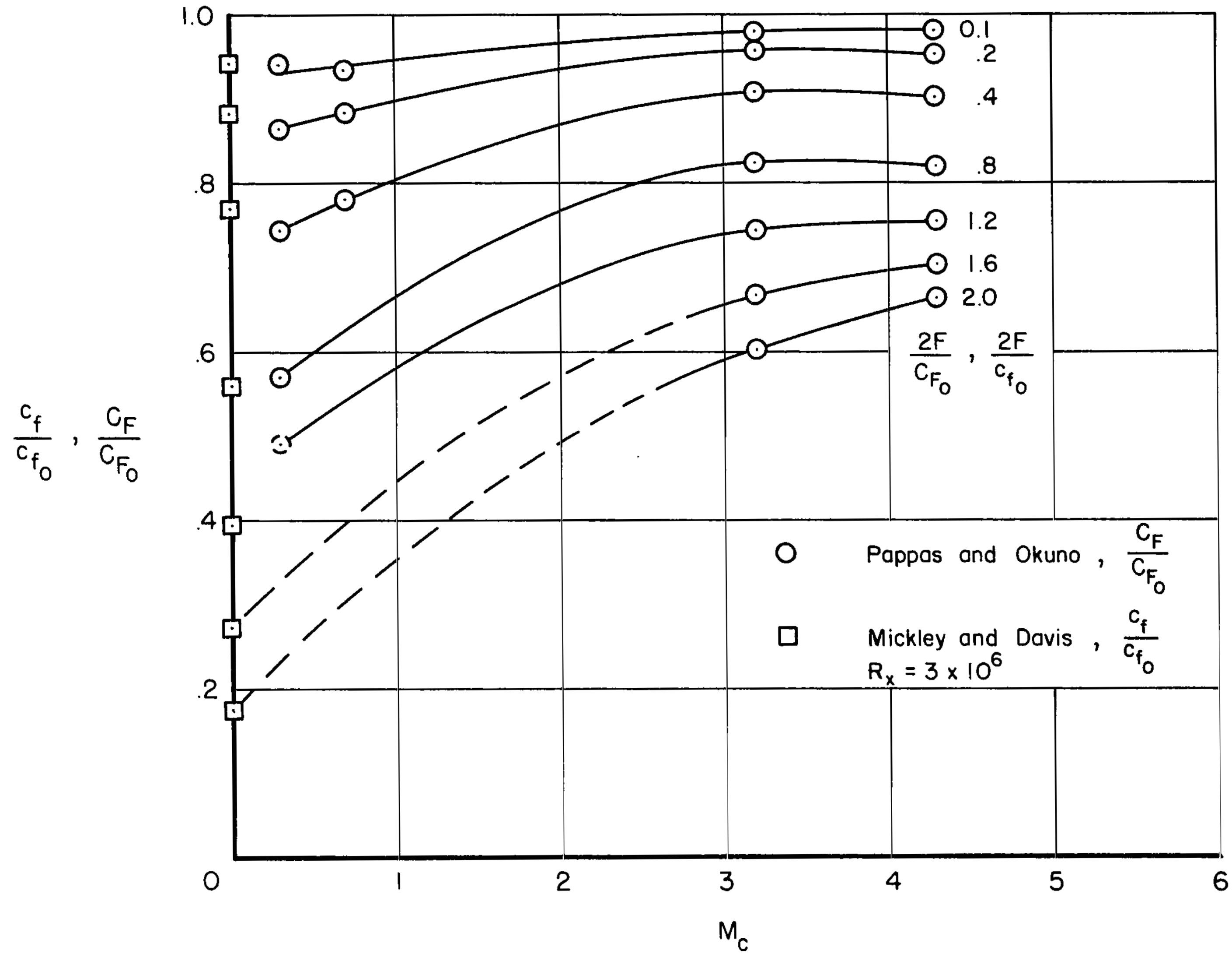
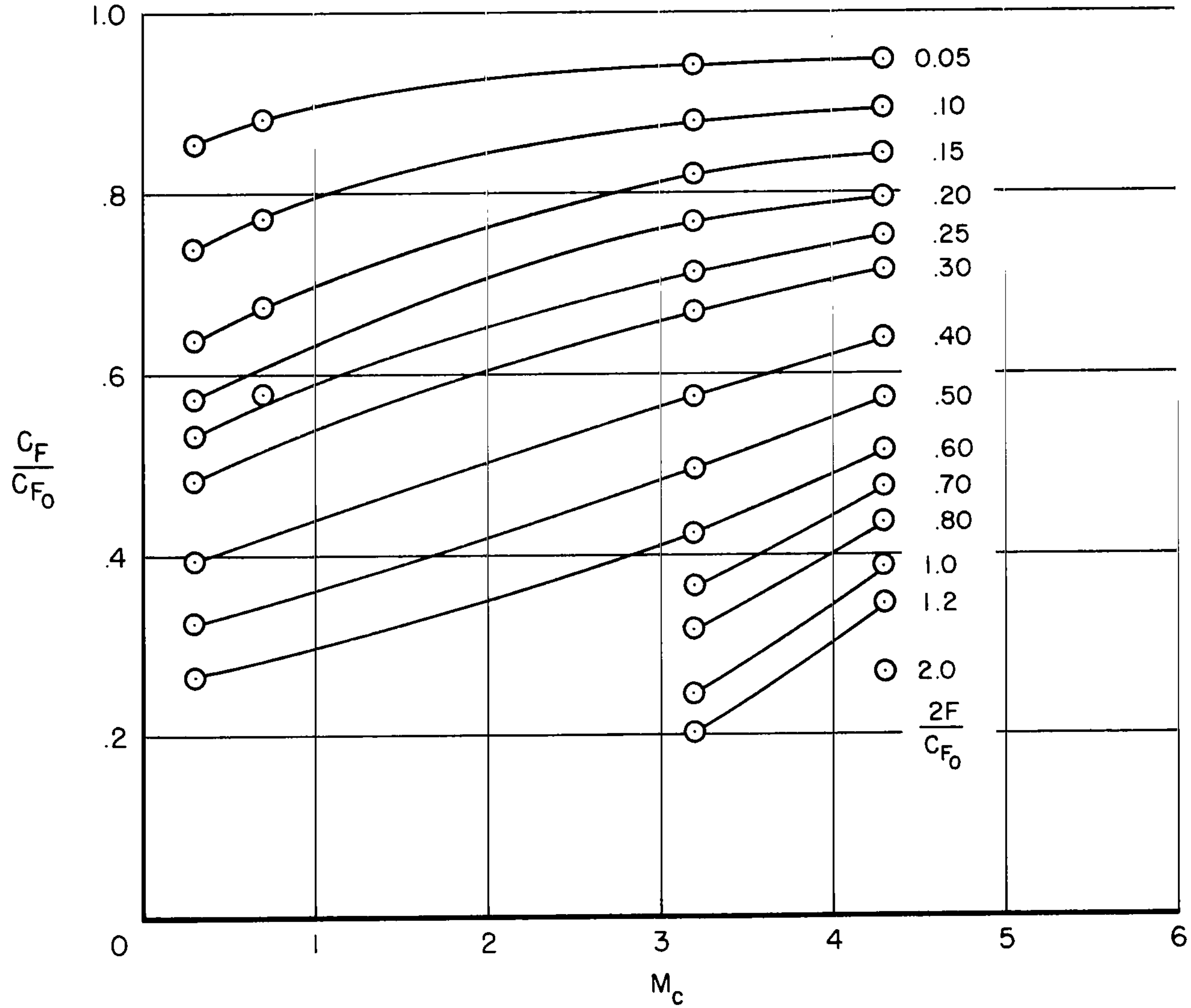


Figure 1.- Cone skin-friction model.



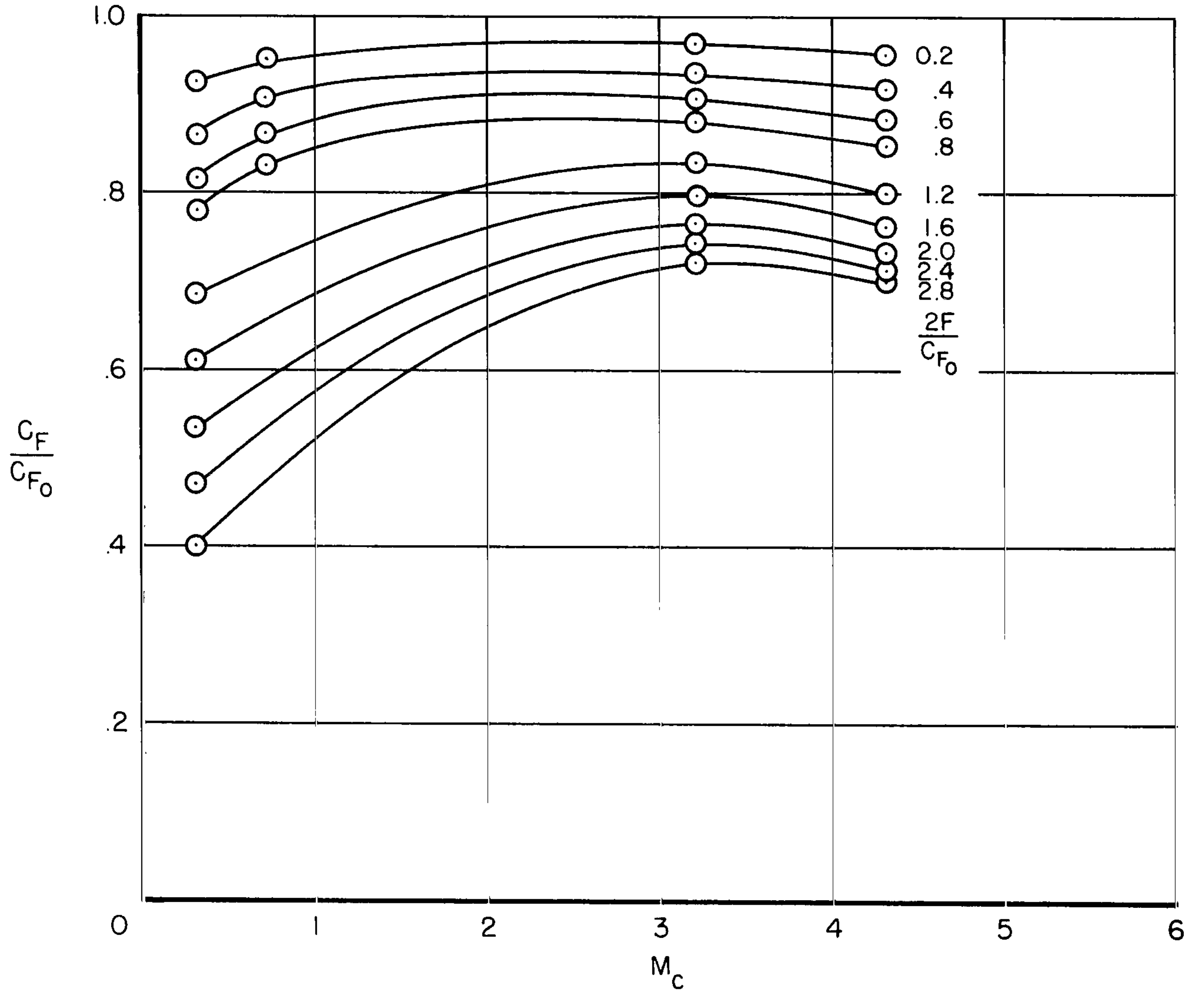
(a) Air injection, $T_w \approx T_r$.

Figure 2.- Effect of Mach number on the reduction in skin friction.



(b) Helium injection, $T_w \approx T_r$.

Figure 2.- Continued.



(c) Freon-12 injection, $T_w \approx T_r$.

Figure 2.- Concluded.

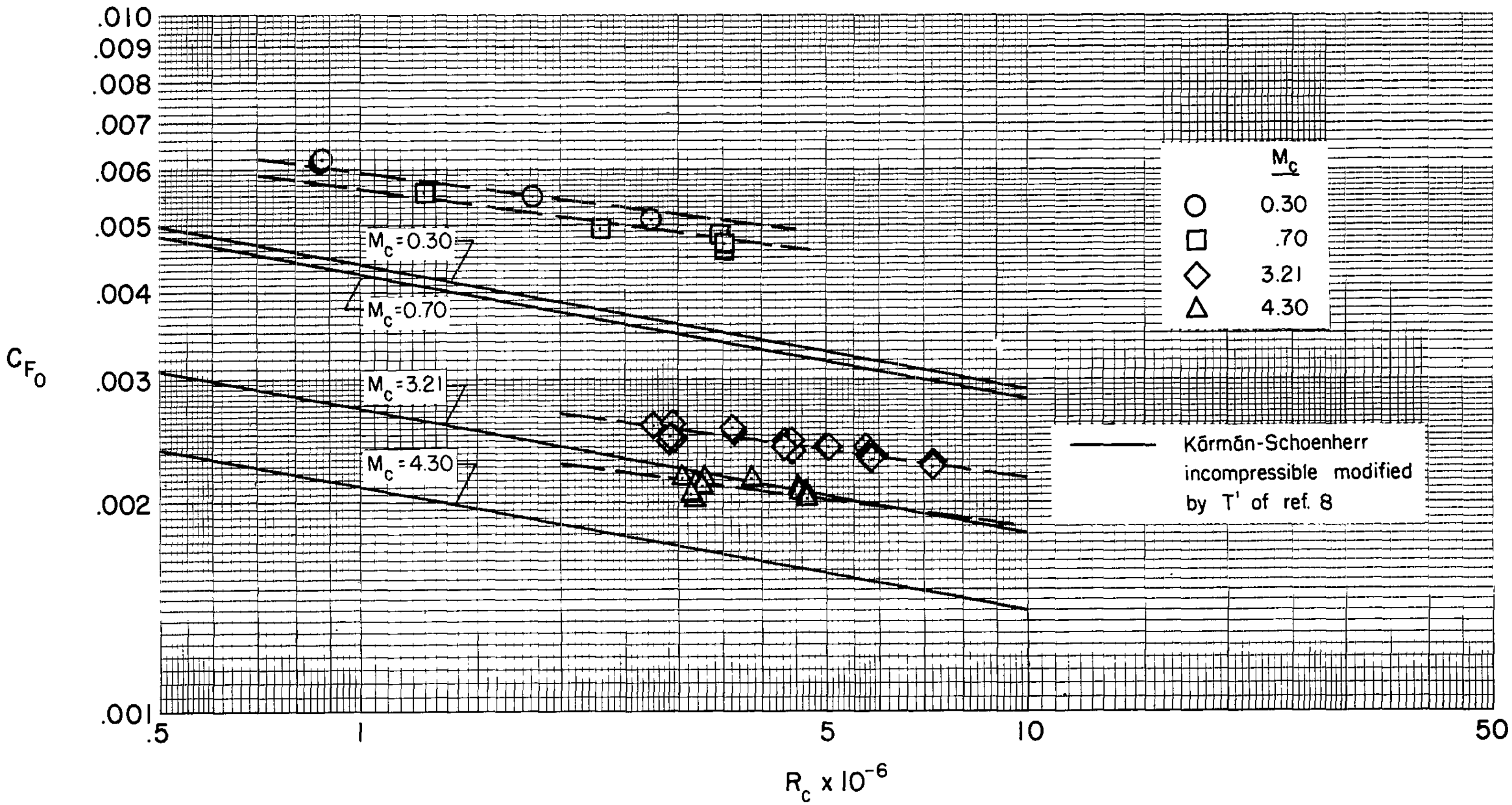


Figure 3.- Average skin-friction coefficient without injection, 15° sharp cone; $T_W \approx T_r$.

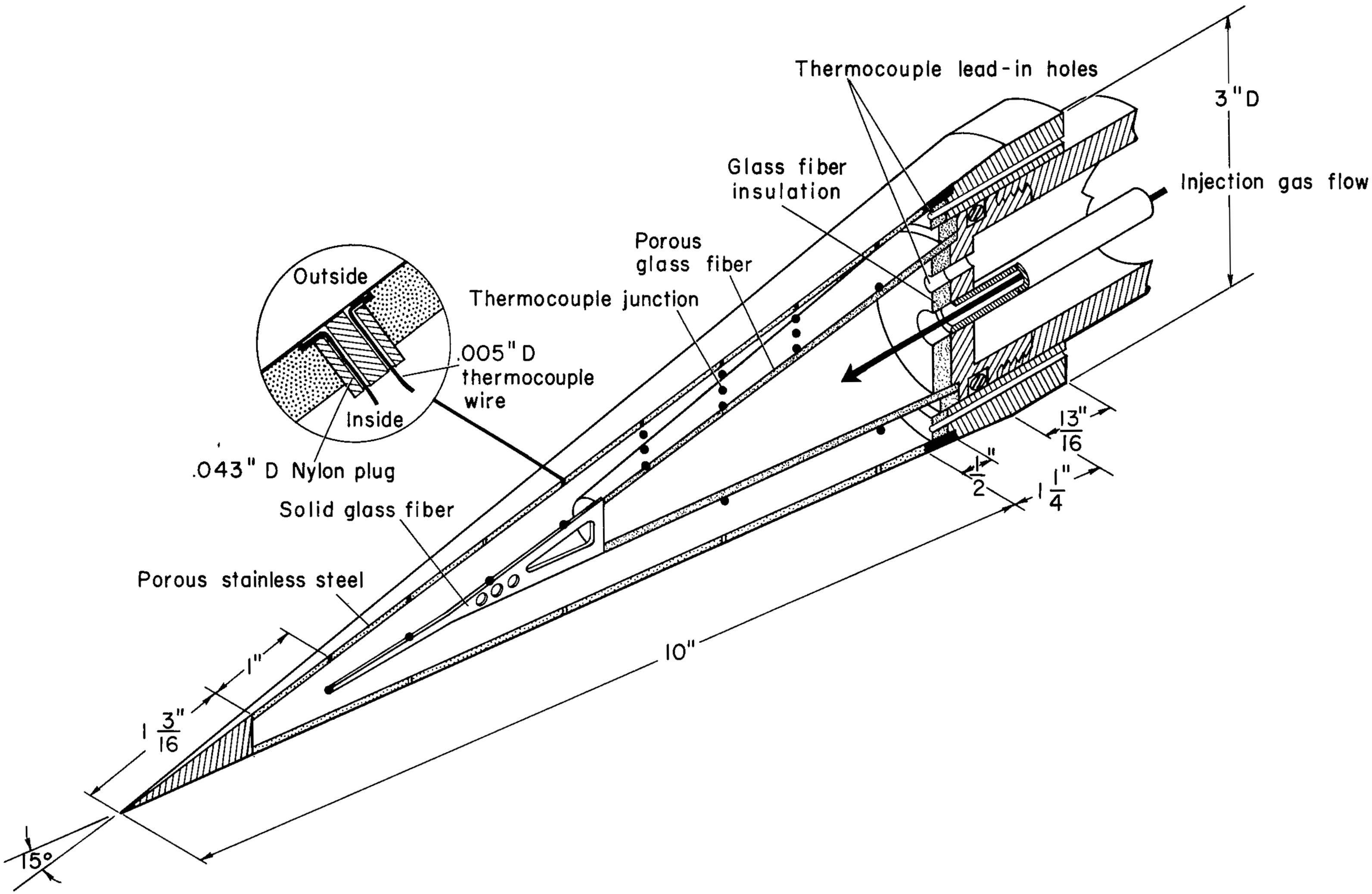
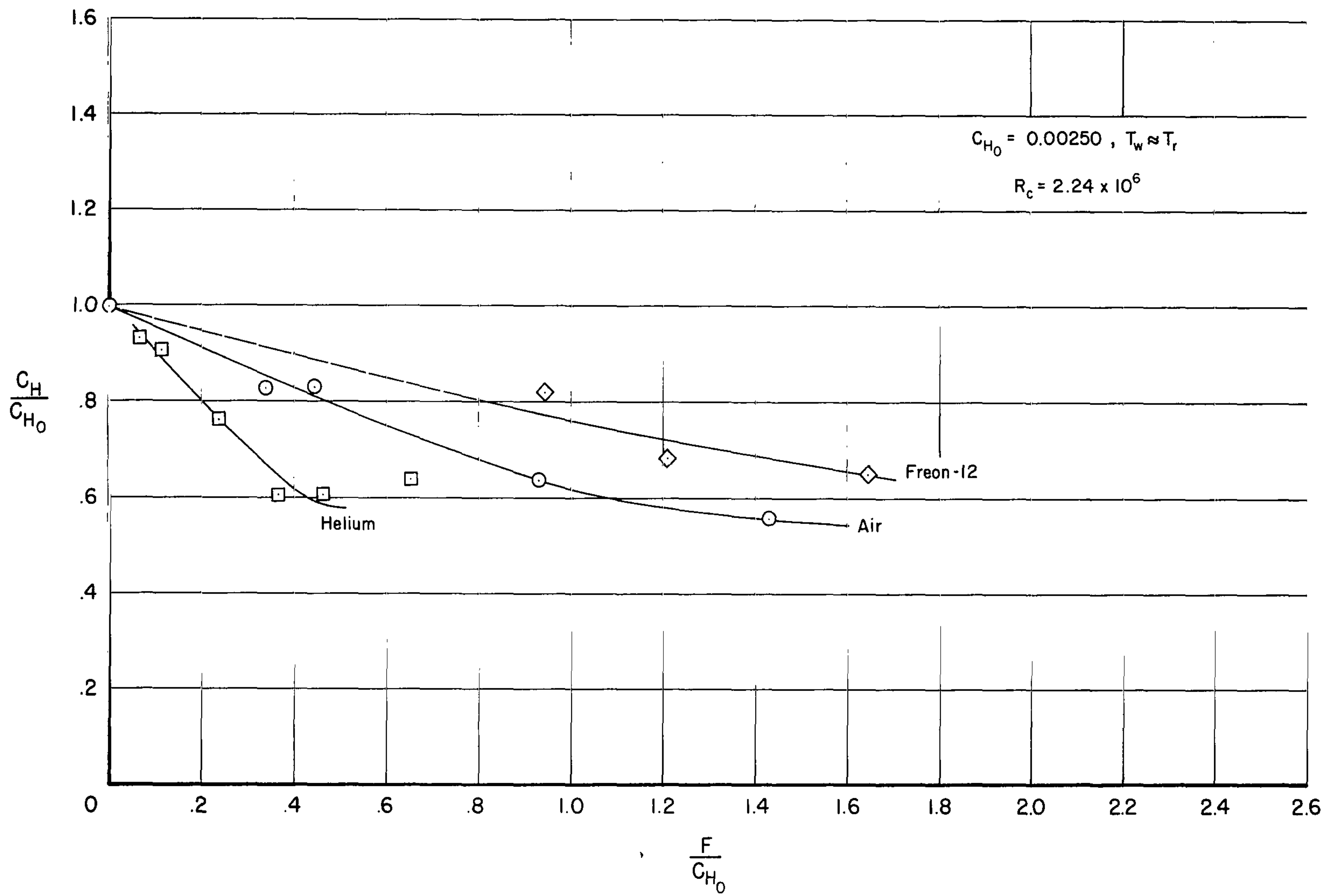
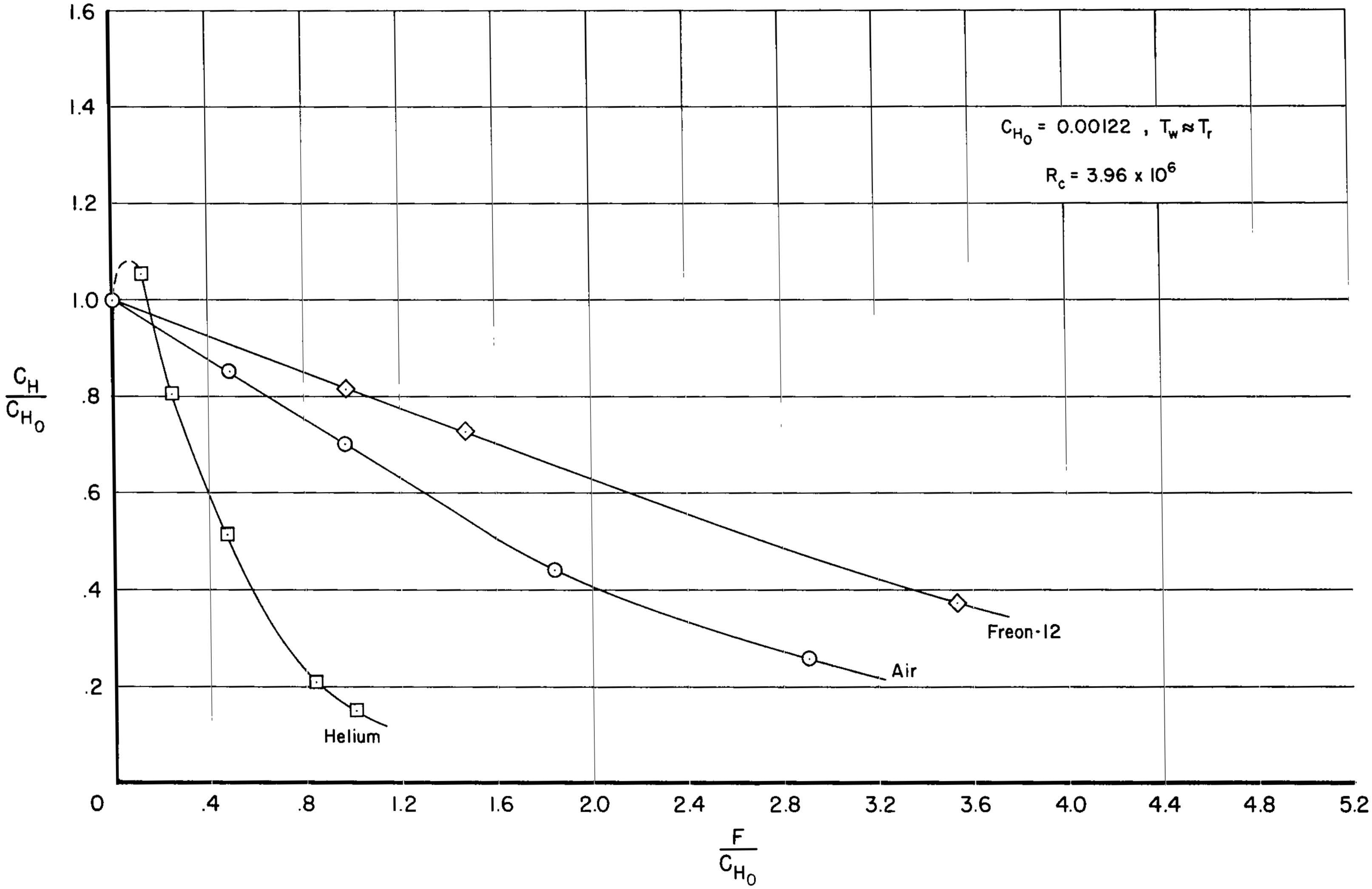


Figure 4.- Cone heat-transfer model.



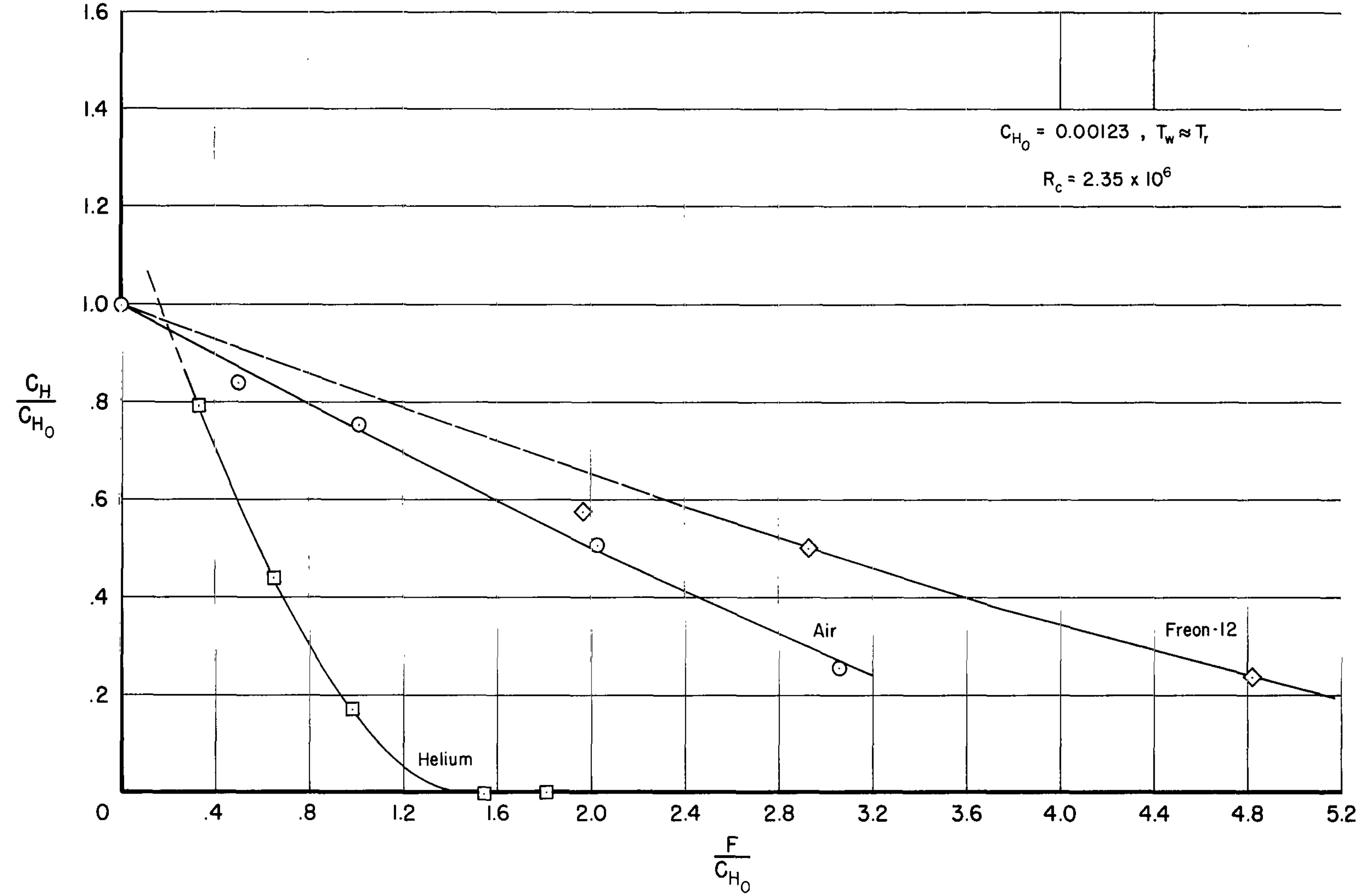
(a) M_c = 0.7

Figure 5.- Effect of gas injection on average Stanton number.



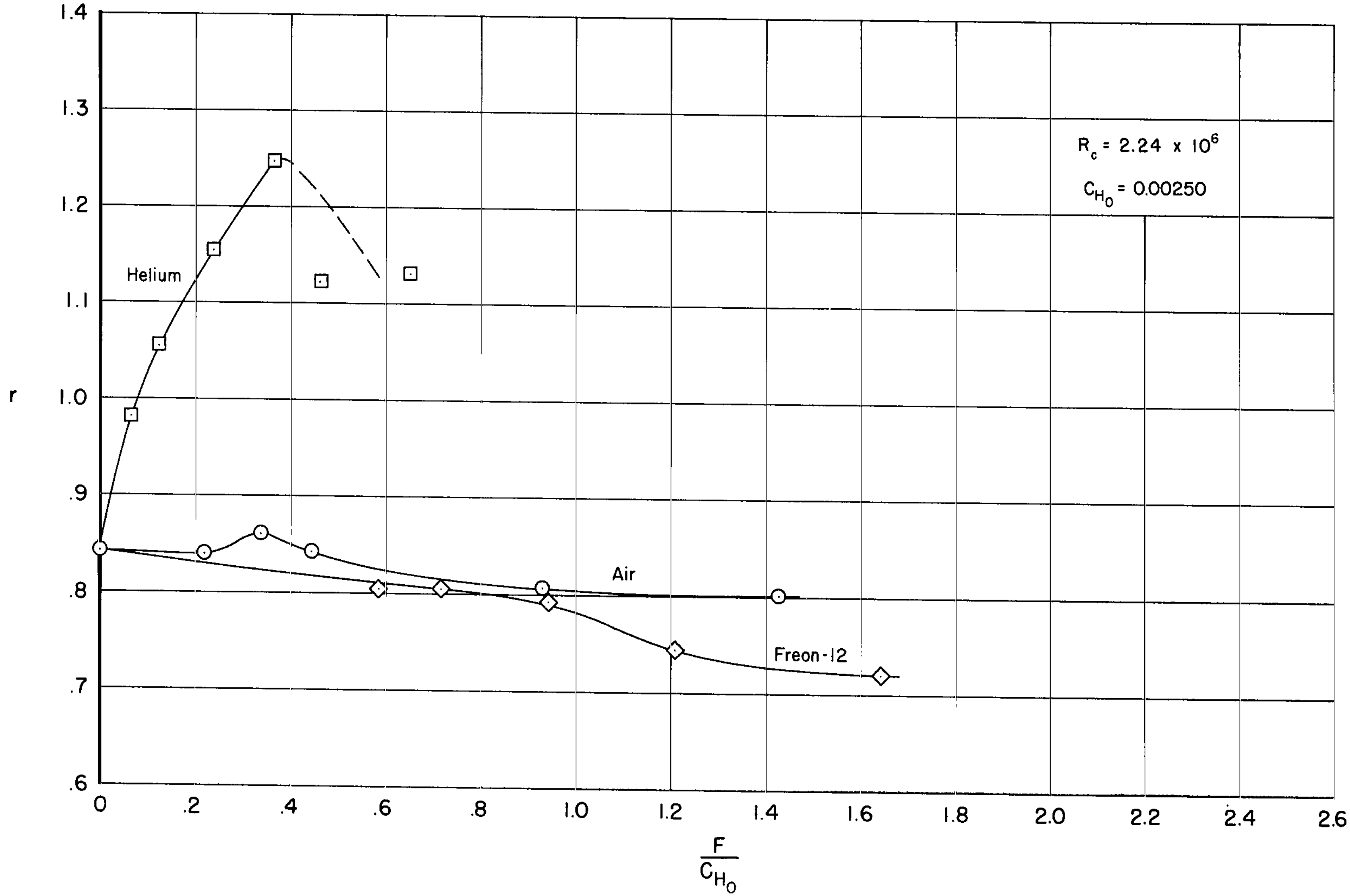
(b) M_c = 3.67

Figure 5.- Continued.



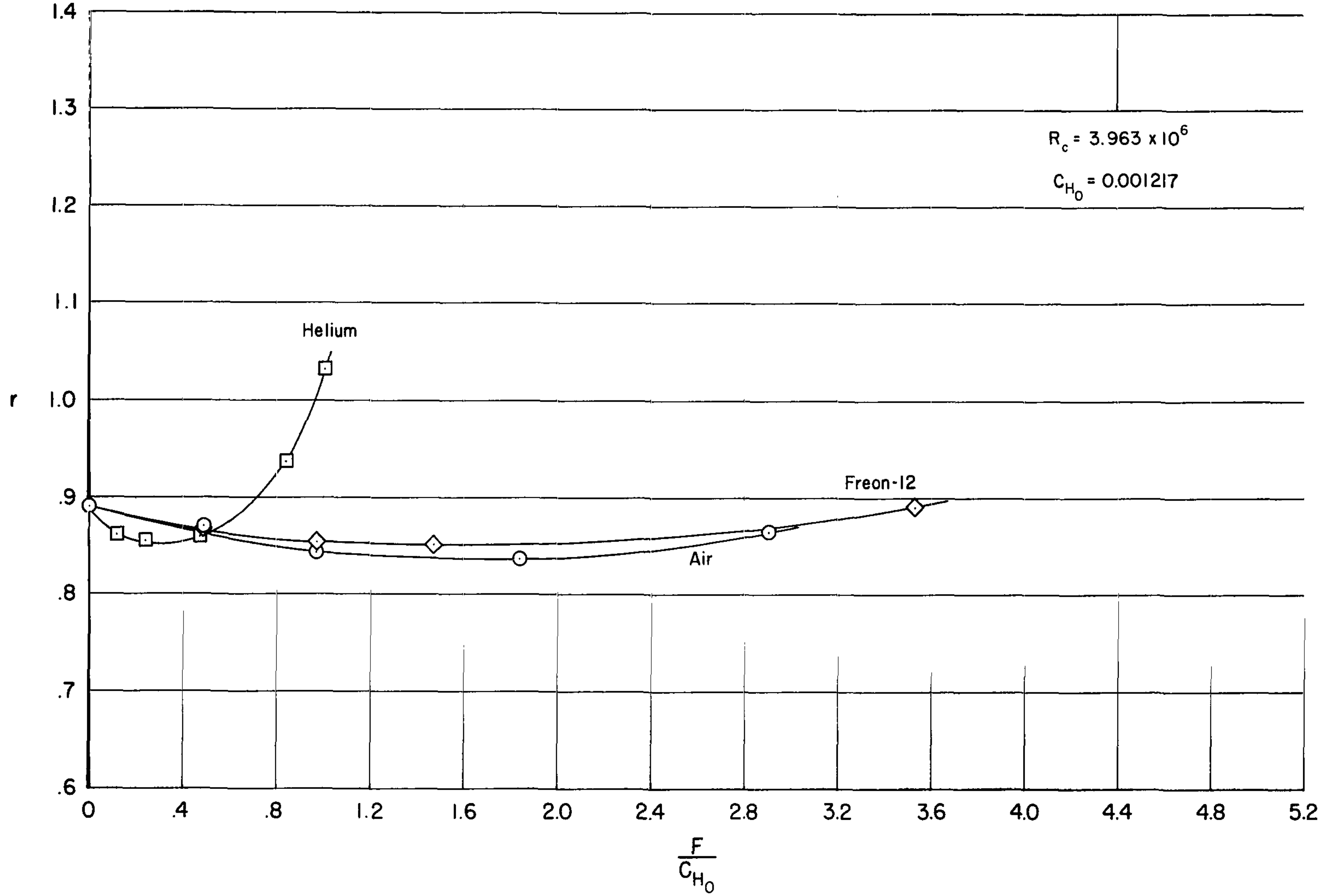
(c) M_c = 4.35

Figure 5.- Concluded.



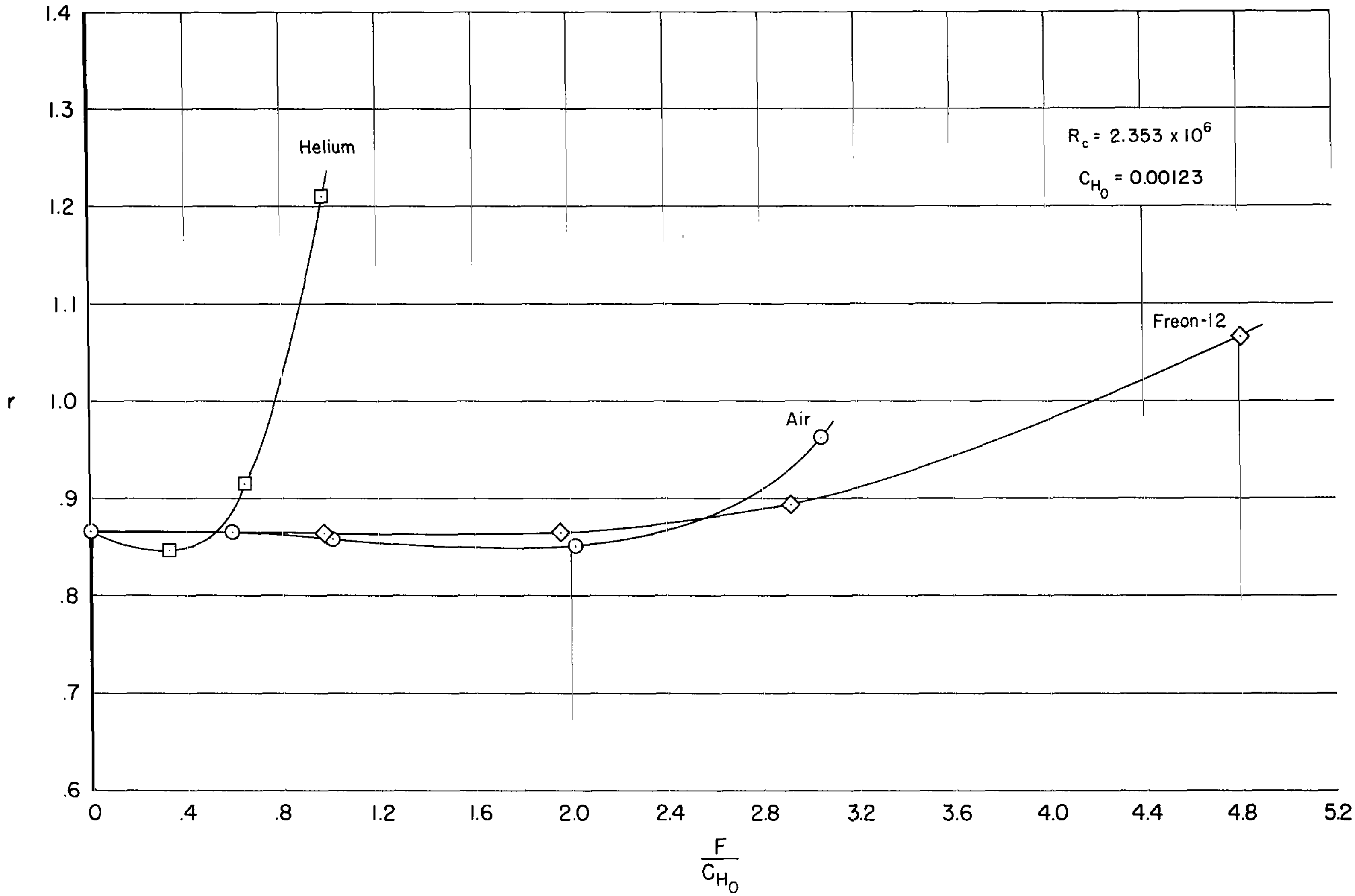
(a) $M_c = 0.7$

Figure 6.- Average recovery factor with gas injection.



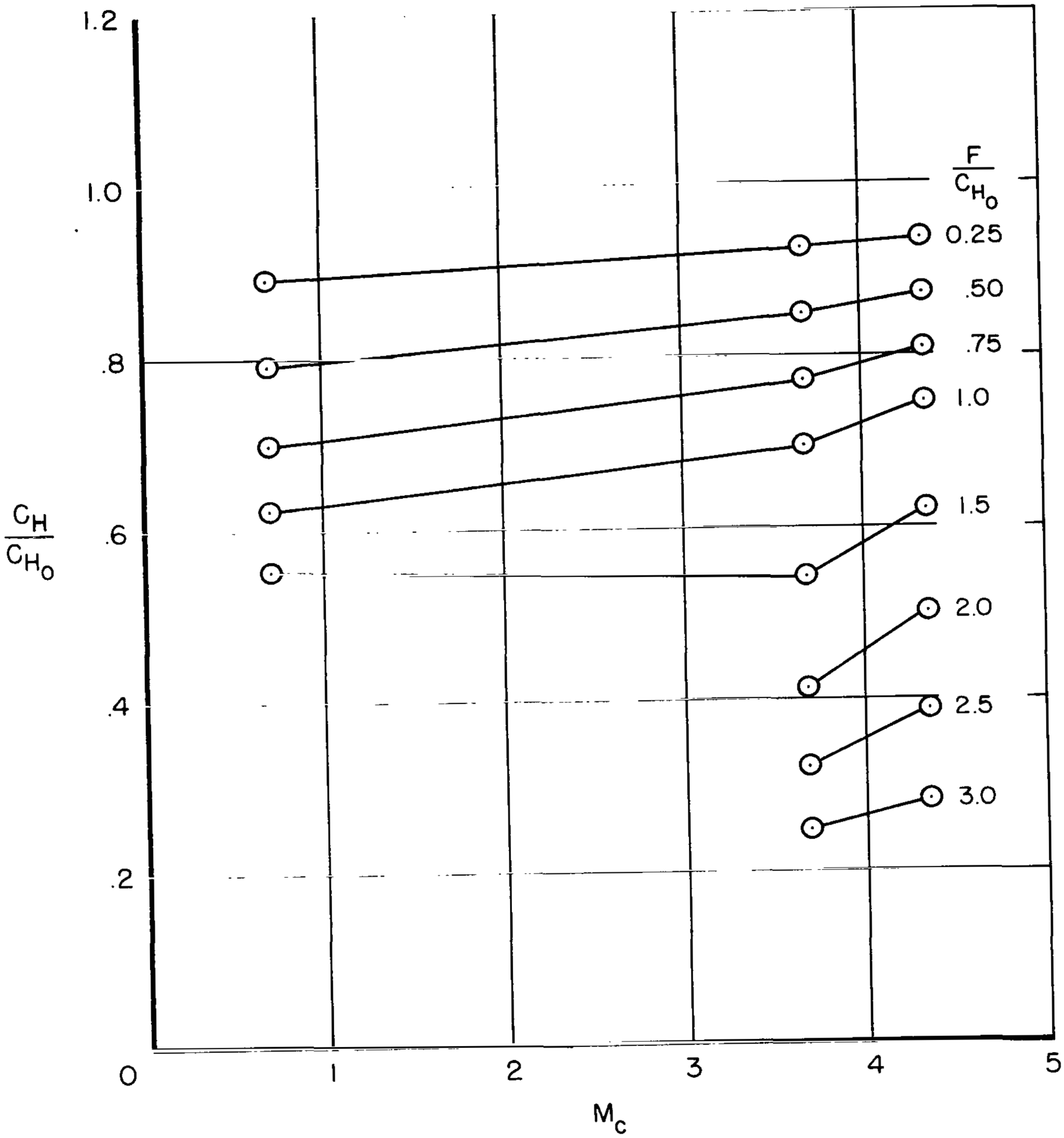
(b) $M_c = 3.67$

Figure 6.- Continued.



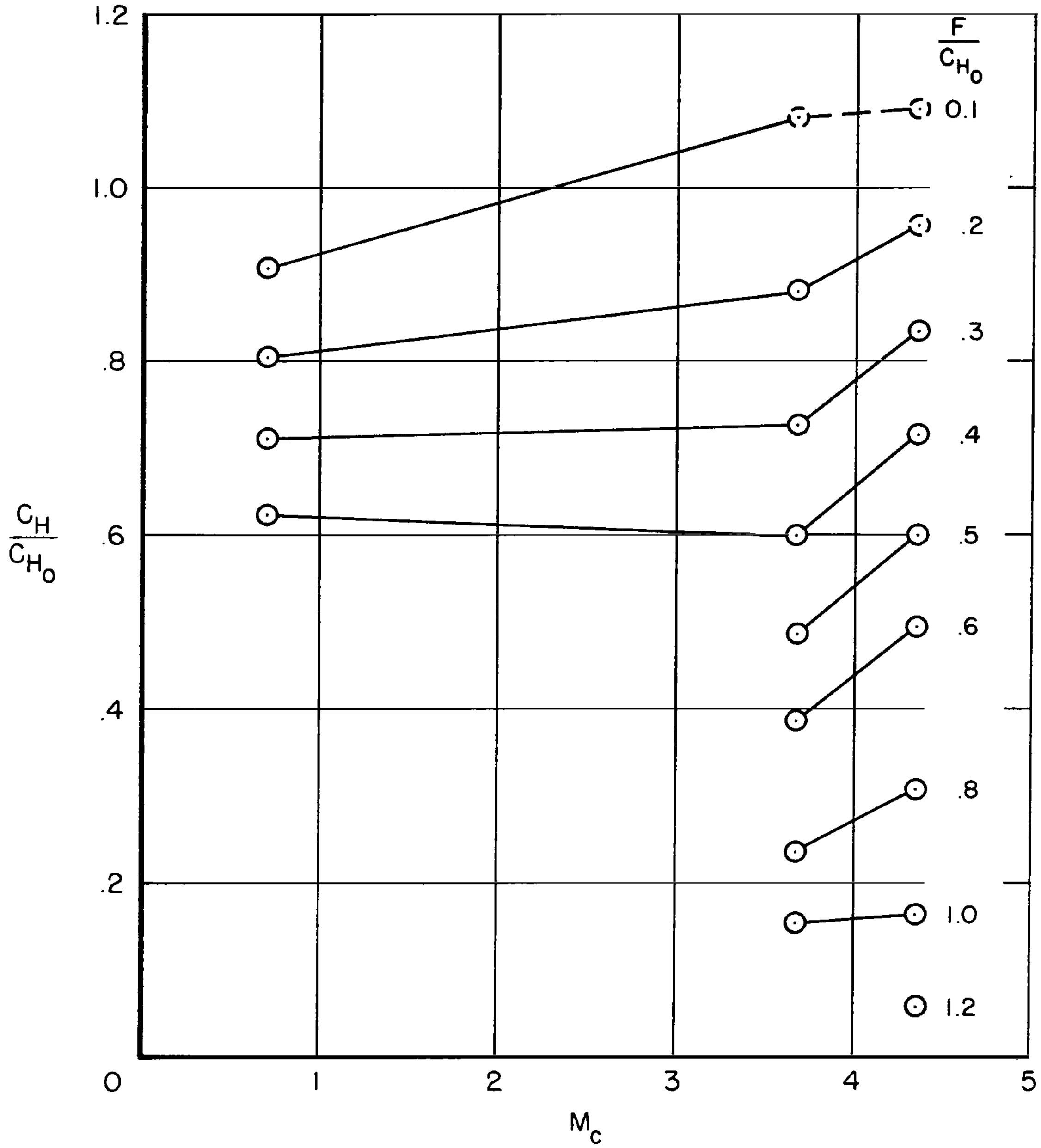
(c) $M_c = 4.35$

Figure 6.- Concluded.



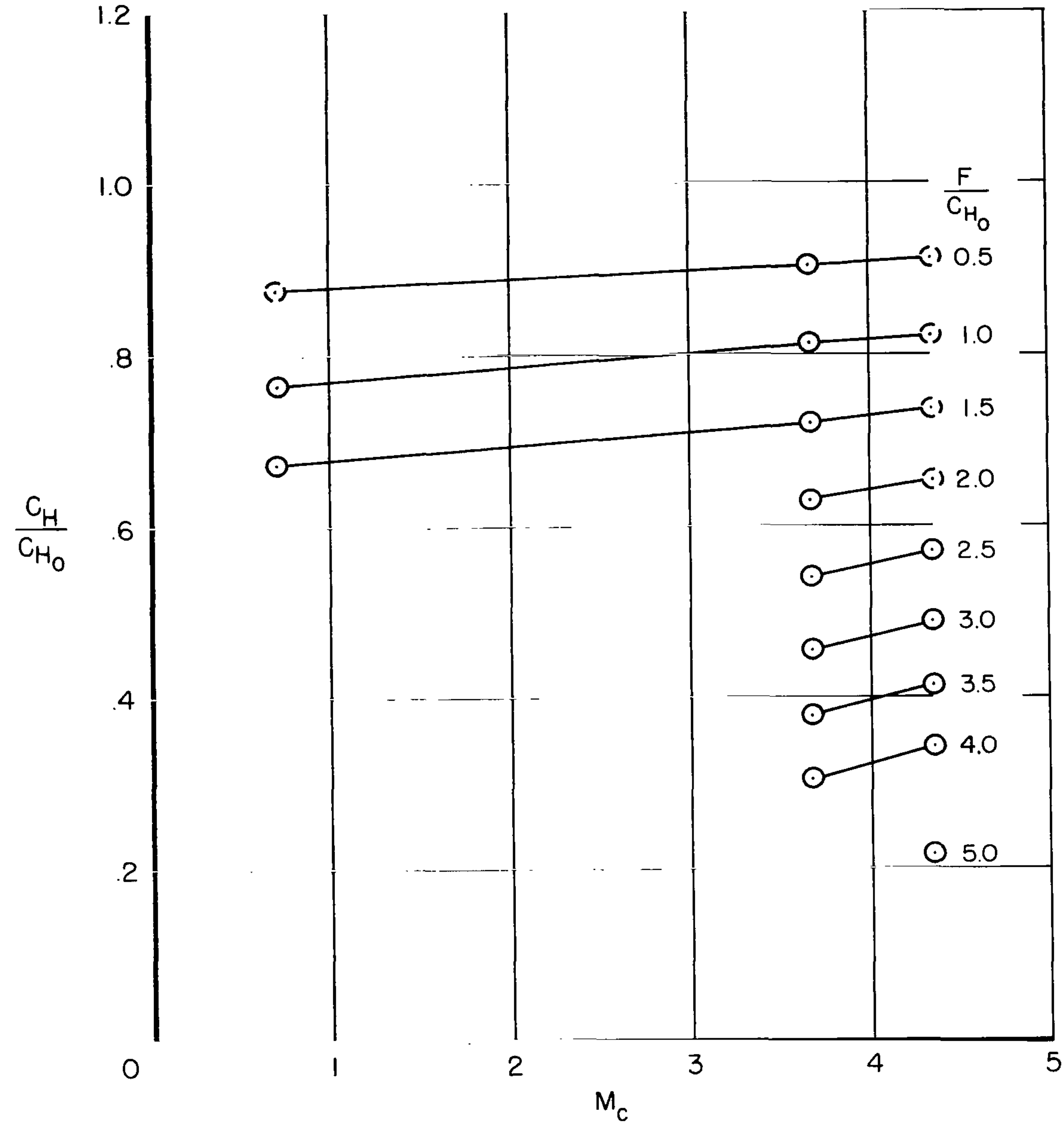
(a) Air injection.

Figure 7.- Effect of Mach number on reduction in Stanton number.



(b) Helium injection.

Figure 7.- Continued.



(c) Freon-12 injection.

Figure 7.- Concluded.

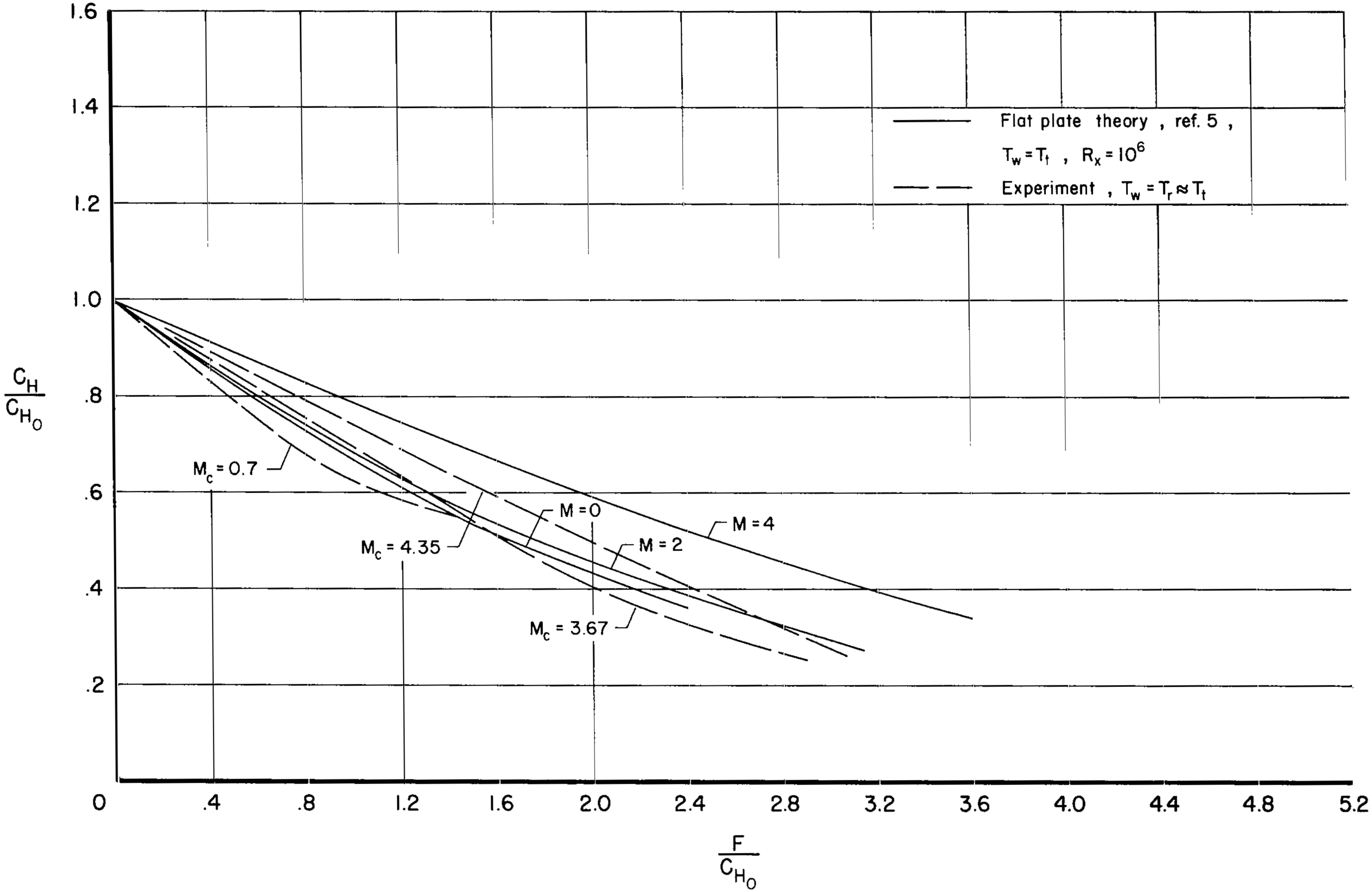
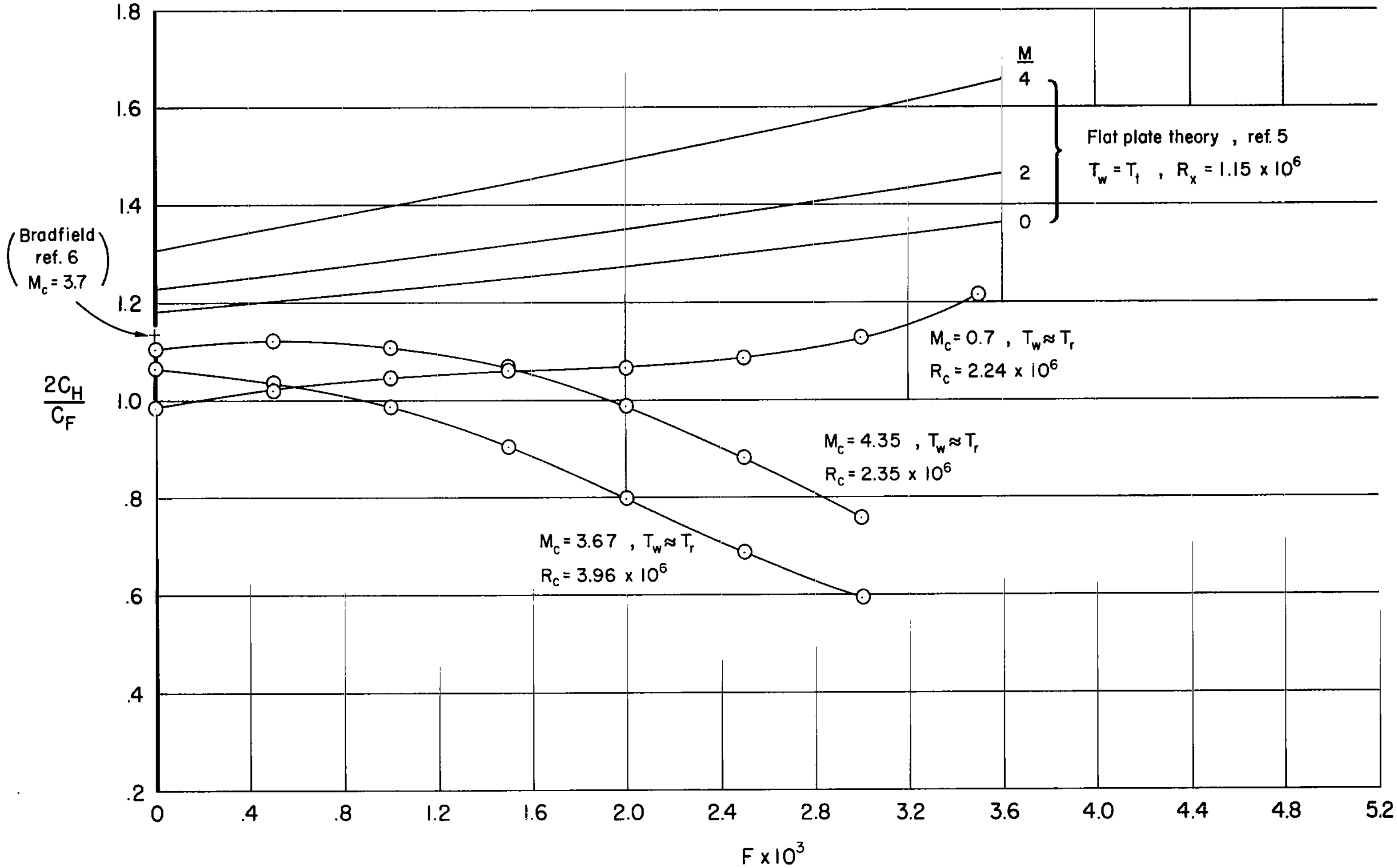
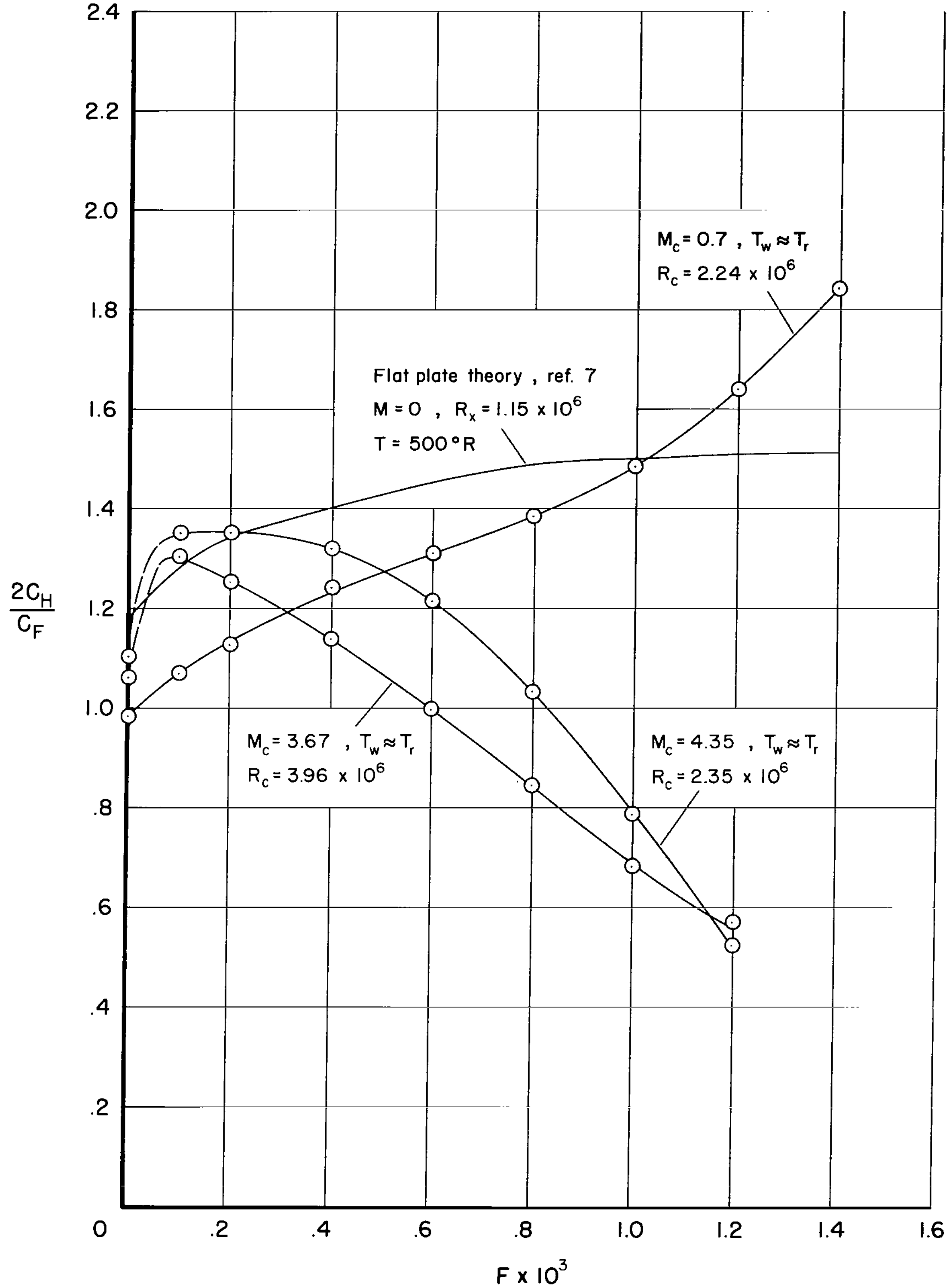


Figure 8.- Comparison of Stanton number reduction of experiment with theory for air injection.



(a) Air injection.

Figure 9.- Reynolds analogy factor variation with gas injection.

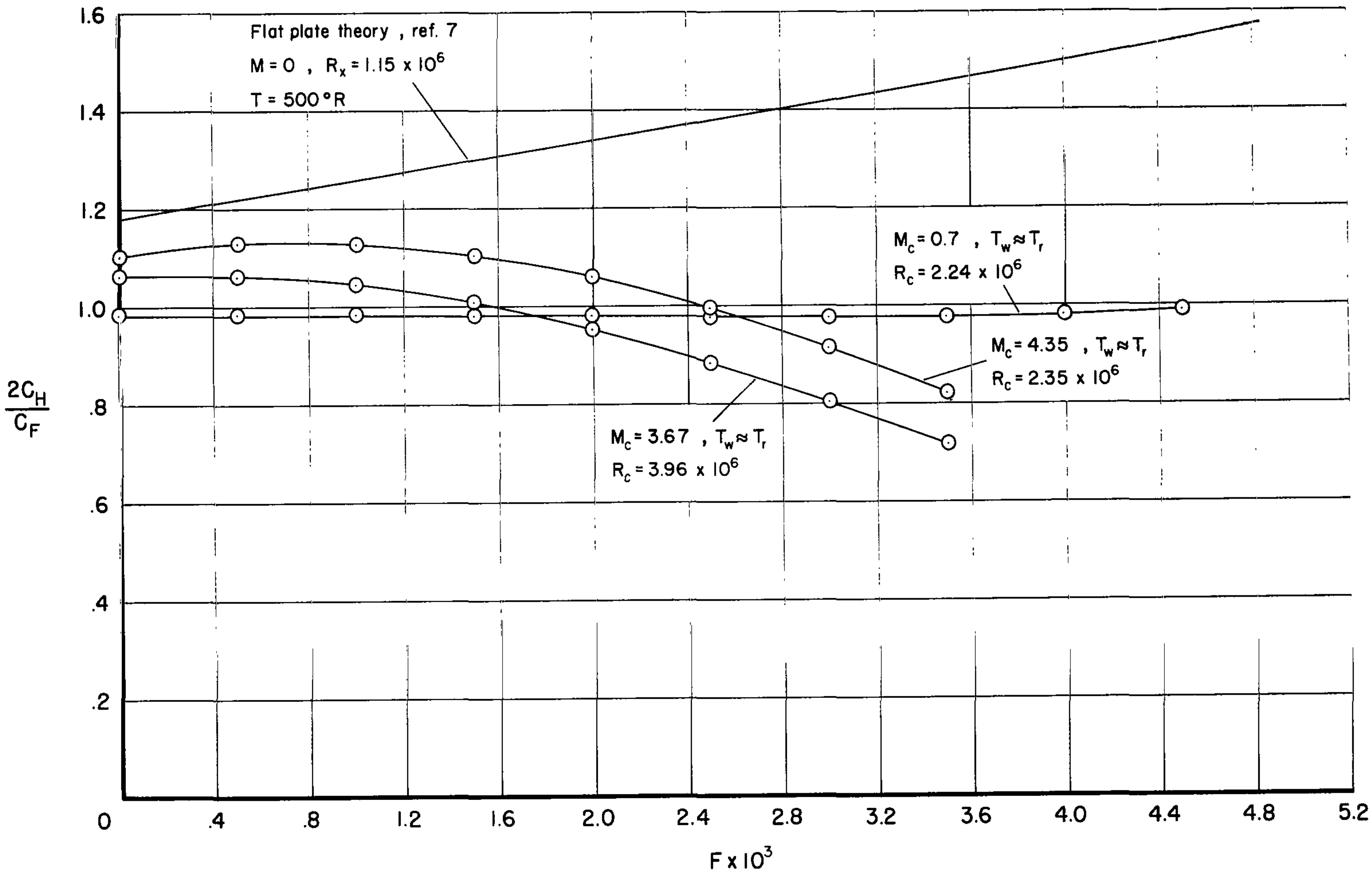


(b) Helium injection.

Figure 9.- Continued.

NASA-Langley, 1965

A-2056



(c) Freon-12 injection.

Figure 9.- Concluded.

2/22/85

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546