VERY LARGE METHANE JET DIFFUSION FLAMES

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Abstract

Methane jet diffusion flames with heat release rates approaching 500 MW in both subsonic and supercritical configurations have been studied regarding lift-off height and flame height and absolute flame stability.

Lift-off heights are in line with small scale literature results, i.e., most of the data exhibit an L_f/U_e value between 2.5 and 5 ms. L_f is the lift-off height and for the choked situation U_e is the resulting velocity at the exit diameter D_e after a hypothetical isentropic expansion through a converging-diverging nozzle to atmospheric pressure. Although the ratio of flame height to actual orifice diameter approached 600 in the supercritical regime, the correlated data are suggestive of relatively similar flame heights (H_f) than those obtained at laboratory scale, $(H_f - L_f)/D_e$ approximately equal to 200.

Flames from orifices up to D = 38 mm could be blown off with sufficient gas pressure. For D = 45 mm the flame could not be blown off for stagnation pressures as high as 3400 kPa. Data from tests at 38 mm and smaller diameters allow an accurate extrapolation, for defining a stability envelope, leading to a predicted critical orifice size of 42 mm for absolute flame stability for CH_4. Failure to sustain ignition of gas from a 1 mm diameter aperture in a reservoir at 12,000 kPa is consistent with the shape of the upper portion of the locus of the derived stability curve.

INTRODUCTION

Interest in gaining further understanding about the behavior of methane jet diffusion flames has been motivated by studies related to fire safety and fire suppression of well blowout fires on offshore structures. In the event of an accidental uncontrolled release of liquid and gas hydrocarbons during well drilling or workover operations, fires often occur. These fires are characterized by a high momentum jet flame lifted above the opening from which the fuel is flowing generally at very high pressures. Even though the effluent from hydrocarbon wells contains both gas and liquid hydrocarbons mixed with varying amounts of drilling fluids and solid debris, this study deals only with the more idealized cases of a gas well blowout fire characterized by the release of methane gas from a high pressure reservoir.

Little quantitative data are available that predict the flame dimensions and radiative output from large methane jet flames especially those from underexpanded supersonic fuel streams. This study is directed at a detailed quantification of the flame dimensional characteristics and stability. Other work related to controlling gas well fires with water sprays to reduce flame radiation and extinguish the flame has been reported previously[1,2]. The data base provided here will be applicable not only to well safety but to the petro-chemical industry in general where the storage and process of high pressure hydrocarbons necessitates an awareness of associated safety issues.

INSTRUMENTATION AND PROCEDURES

Test data for these methane jet flame studies were collected in three separate test facilities, all of similar design but different scale. Each consisted of a high pressure methane gas supply from which a regulated amount of methane flowed into a metering section of pipe containing valves and a commercial flange-tap orifice meter for measuring flow rate. After the metering section the flow passes through a relatively long length of 102 mm to 204 mm diameter pipe, depending on the scale of the experiment, to an exit contraction formed by a sharp edged orifice disk that vented the methane flow vertically into the atmosphere. Test data for fires up to 20 MW were collected using the test facility at the National Bureau of Standards (NBS) in Gaithersburg, Maryland. Fires up to 200 MW were conducted at the facility constructed by Energy Analysts, Inc. in Norman, Oklahoma. The largest methane fires of 470 MW were studied at the Blowout Prevention Research Well Facility at Louisiana State University (LSU) in Baton Rouge, Louisiana.

Flame heights and liftoff distances were measured using still photographs, video recordings and a surveying transit when available at both the NBS and LSU facilities. The same data was measured from 16 mm films of the test fires and adjacent support towers at the Oklahoma test facility.

DATA HANDLING AND CHOKED FLOW

Procedure for reducing data consisted of finding the effective Mach number of the flow assuming an isentropic expansion,

$$M_e = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{p_o}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (1)$$

where p_o is the measured pressure upstream of the vent orifice. p_∞ is atmospheric pressure and the ratio of specific heat, γ, for methane is 1.3, assumed constant irrespective of pressure ratio. For all area combinations of exit orifice and pipe used here the pressure, p_o, was essentially the stagnation pressure. For p_o/p_∞ below the critical, the Mach number calculated was representative of the orifice exit flow conditions. For supercritical conditions the procedure used by Kalghati[3] and Annushkin and Sverdlov[4] was followed. Sonic conditions exist at the exit plane of the orifice but the pressure is larger than atmospheric and hence some sort of expansion must take place. The orifice is conceptually replaced by a converging-diverging nozzle the throat of which has a diameter equal to the diameter of the orifice, D. Sonic conditions will exist here and the flow will expand supersonically to atmospheric pressure at the exit of the nozzle whose conditions will be designated by the subscript e. All of those conditions are given by the normal one-dimensional isentropic flow relations, e.g., the diameter at the exit of the nozzle, D_e, is:

$$\frac{D_e}{D} = \frac{1}{\sqrt{M_e}}\left[\frac{2 + (\gamma - 1)\, M_e^2}{\gamma + 1}\right]^{\frac{\gamma+1}{4(\gamma-1)}} \quad (2)$$

Knowing the exit flow Mach number (M_e) and area, all parameters of interest are determined. The effective exit velocity is M_e times the local sound speed, i.e.,

$$U_e = M_e \sqrt{\gamma R T_o/\left(1 + \frac{(\gamma-1)}{2} M_e^2\right)} \quad (3)$$

with R, the gas constant and T_o the upstream stagnation temperature.

Other models of the expansion of these sonic jets exist in the literature. Here we have chosen simple isentropic flow and have ignored the complicated barrel shock structure and interactions with the cold supersonic flow after the expansion.

RESULTS

Lift-Off and Flame Height

Figure 1 shows the vertical distance between the bottom of the visible luminosity and the plane of the orifice, i.e., the lift-off height, plotted against the calculated isentropic Mach number. L_f rises with M_e or flow velocity, U_e, and amongst the scatter seems to be independent of exit diameter. Nor does any kind of flow transition appear to be taking place in going supercritical. That is, there does not appear to be any dramatic change in the trend of the data before and after criticality. The two lines shown represent the constancy of flame lift-off distance to effective exit gas velocity. This is a kind of transit time for a gas parcel to reach the beginning of the luminous portion. The harder one pushes out the gas reflected in higher velocities the further away the flame will reside, independent of orifice diameter. The two curves on the figure are for:

$$L_f/U_e = 2.5 \text{ ms and } 5 \text{ ms}$$

which is in line with the estimate of Peters and Williams[5] of 3.6 ms and somewhat higher than the value determined by Kalghatgi[6] based upon laboratory scale experiment (2.2 ms). The observed lift-off heights of several meters, as seen on Fig. 1, graphically illustrates the scale involved in these experiments.

For methane flames at laboratory scale an L_f/D of about 50 is where flame blowoff is expected to occur[5]. Note the two 51 mm points at about $M_e = 2.65$ on Fig. 1. Those points represent an L_f/D above 80 indicating the degree of stability that can be obtained in large diameter, large stagnation pressure diffusion flames. This data coupled with the other set of high M_e data, the 45 mm relatively low L_f points, are reminiscent of the bimodal-bistable character of liftoff noted at laboratory scale. High and low positions of liftoff, seemingly to occur in random fashion, have been noted previously at small diameters[8]. We can perhaps assume, for now, that the large scatter noted on Fig. 1 is not a particular characteristic of supercritical diffusion flames. Much more systematic study of that phenomenon can be performed at convenient laboratory scale.

Figure 2 shows the flame height, H_f, the vertical distance from the plane of the orifice to the extremity of visible luminosity, normalized by the actual orifice diameter, plotted against, again, the effective Mach number of the flow. Diameter appears to scale the data adequately, as is well known. There may or may not be a transition in the data at criticality based on the plot of the data seen in Fig. 2. A lot of speculation exists as to the magnitude of the flame height/actual diameter ratio for supercritical flows[7]. The data points at around $M_e = 2.7$ and $H_f/D = 400$ and above can be used to "calibrate" various models of the behavior of hydrocarbon diffusion flames from underexpanded supersonic jets.

The curve on the figure appears to bridge the transition between sub- and supercritical orifice flow. For the subcritical regime $M_e < 1$, at the high momentum end of the Froude number spectrum flame height becomes a constant, independent of flow rate and for CH_4 the classical result[11] is approximately

$$\frac{H_f - L_f}{D} = 200 \qquad (5)$$

where D is the actual orifice diameter. ("Scaled" diameters due to momentum effects, e.g., the square root of the density ratio, are already contained in the expressions which lead to the value 200.) On Fig. 2 that is the horizontal line at and just below criticality, $M_e = 1$. If one goes further to the left into the lower flow regime buoyancy will begin to become apparent and the flame height will no longer be constant but will decrease as the flow rate of gas is decreased.

Our interest here of course is for $M_e > 1$ and the simplest way of attempting to characterize this region is to use the subsonic result Eq. (5), but replace D by D_e, the fictitious exit diameter resulting after the supersonic expansion. By replacing D in Eq. (5) by D_e and multiplying by Eq. (2) we can plot H_f/D which is the curve on Fig. 2 for $M_e > 1$. From Fig. 1, L_f will not scale with D so an arbitrary L_f/D has to be assumed in order to construct the line. We choose an arbitrary 15% of flame height as the lift-off. This value is consistent with the data in Fig. 1, falling between the high and low values of the high M_e data. (The 51 mm data discussed previously having an

L/D of 80 represents about 80/400 or about 20% of flame height. The lower 45 mm points represents a lift-off of about 10% of flame height.)

The agreement between the modified-to-D_e Eq. (5) and the data is reasonable to the point that a more elaborate scheme or analysis is not warranted. Both in Fig. 1 where the lines involving U_e, the effective velocity after the hypothetical isentropic expansion, show good agreement with small scale subcritical L_f/U_e values, and here in Fig. 2, where the sub-critical, modified to accommodate the expansion in terms of Eq. (2) for D_e, there appears to be justification for the present method of handling the choked flow data. Using an alternate scheme for estimating D_e would obviously yield different results, e.g., H_f/D_e would be less than 200 for expansions resulting in larger values of D_e/D.

Discharge Coefficient

In order to account for losses due to contraction and friction associated with gas flowing through orifices, which will reduce the flow rate somewhat from that which is calculated using the one-dimensional isentropic relations, a discharge coefficient relating the actual to the theoretical flow rate can be determined. In the Kalghatgi[3] study the burners were straight tubes and the losses associated with those were determined to be negligible. Unlike nozzles or straight tubes where the diameter of the jet will be practically constant, for the most part, the flow through sharp edged orifices will require correction.

Figure 3 shows the discharge coefficient as a function of pressure ratio, i.e., atmospheric pressure divided by the absolute pressure in the pipe just upstream of the orifice. The discharge coefficient is equal to the actual standard volumetric gas flow rate times the standard density divided by the calculated or theoretical mass flow rate per unit area,

$$w/A = \sqrt{\gamma/R}\,\frac{P_o}{\sqrt{T_o}}\,\frac{M_e}{\left[1+\frac{\gamma-1}{2}M_e^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}} \qquad (6)$$

and the effective discharge area, $\pi D_e^2/4$. This denominator reduces to Fliegner's formula for the maximum flow, i.e., sonic conditions at the orifice, D.

At small pressure differences the data approaches the usual incompressible result of about 0.6. As the stagnation pressure increases the losses decrease, the coefficient rising through the critical regime to somewhat below about 0.9 at the extreme of the choked flow conditions. Shown with the data for comparison is the solid line representing small scale, sharp-edged orifice data for air due to Perry[9]. In general, the agreement is good considering the normal inaccuracies associated with field test data in comparison to more easily, and therefore, presumably, more carefully obtained and reproducible laboratory data. Through a factor of about twenty times in size there appears to be no observable effect due to scale nor to molecular structure of the gas.

For reasonable accuracy, then, Eq. (6) coupled with Fig. 3 can provide a means for predicting the flow rate from a break in a high pressure line knowing the area and stagnation pressure. Kalghatgi[3] finds no loss for straight tubes, that is, for no contraction. Figure 3 can be used for sharp contractions. Presumably real breaks ought to fall somewhere between the two extremes.

Blowoff and Absolute Flame Stability

Figure 4 presents the full range of behavior of CH_4 jet diffusion flames regarding their stability to blowoff. Blowoff is simply that point expressed here in terms of exit gas flow velocity, U_e, beyond which a flame can no longer be sustained for that diameter burner, D. For gas flow rates lower than this value the flame exists as a stable lifted flame. For higher flow rates, the lift-off distance appears to become too great for continued self-sustaining combustion - the luminosity disappears, the combustion noise ceases and the flame is gone - one is left with a simple cold jet of gas.

This is the situation for relatively small diameters, the sizes one normally encounters in the ordinary laboratory, the 10 mm D range. The data shown in the lower left corner represented by the plus signs from Ref. 10 are examples. As the nozzle or orifice size increases the requisite velocity of the gas required for blowoff increases proportionately and very quickly one is in the choked flow regime and is beyond the range of the small laboratory both in the amount of gas required and the resulting flame height. The present, D = 38 mm, result at a U_e of 500-600 m/s is using gas at the rate of a standard size, 1A, gas cylinder on the order of every 10 s and prior to blowoff has a flame height of 9 m.

The solid line on Fig. 4 is simply a least squares fit of all the blowoff points, crosses (x) as well as plus sign (+) symbols, in terms of the non-dimensional variables $\bar{U}_e$ and R_h used by Kalghatgi[3] in his pioneering work on blowoff. $\bar{U}_e$ is simply the actual blowoff velocity normalized by the laminar flame speed to accommodate different burning behavior of different fuels, multiplied by (ρ_e/ρ_∞) raised to the 1.5 power. R_h is a Reynolds number with the length scale given by a height above the outlet where the gas and entrained air are proposed to have attained a stoichiometric mixture. For present purposes the important thing is that R_h is almost directly proportional to effective burner diameter, D_e.

Kalghatgi[3] found almost a linear relationship between the velocity of the gas at blowoff and the exit diameter for a variety of fuels. The results were then generalized using:

$$\bar{U}_e = \frac{U_e}{S_u} \left(\frac{\rho_e}{\rho_\infty}\right)^{1.5} \tag{7}$$

and

$$R_H = H\left(D_e\right) \cdot S_u/\nu_e \tag{8}$$

For small diameters, low blowoff velocities the linear relationship found in the non-dimensional variables translates, obviously, directly back into an almost linear relationship in the dimensional variables such as seen on Fig. 4 at low velocities. However, at larger D and U_e the linear-like relationship between (7) and (8) translates into very different behavior in the dimensional space.

The result of the correlation of the plus sign symbols[10] and present cross symbols is an almost linear relation,

$$\bar{U}_e = 0.117\ R_H^{0.763} \tag{9}$$

For small diameters this compares favorably with the linear variation found by Kalghatgi[3] shown by the dashed line on Fig. 4. For CH_4 his results extended only to D = 12 mm and the deviation noted for larger D on Fig. 4 may be due to the disproportionate weighing of the other gases in the correlation, those gases exhibiting higher R_h.

Now, following Kalghatgi[3] and Annushkin and Sverdelov[4], Eq. (9) can be extrapolated beyond where there is data and the entire reversed C-shaped curve shown on the figure can be obtained. The implication of this is dramatic – for increasing flow velocity the locus of the blowout points reaches a maximum and then reverses. There is no longer a monotonic relationship between diameter and velocity. At diameters greater than approximately 42 mm the flame can not be blown off regardless of how high the exit velocity. And just as intriguing, at diameters below 42 mm there exists two values of velocity where a transition from stable flame to blowoff will occur. At a given diameter the flame first blows off at the lower leg and then a flame will be able to be reignited when the upper leg is reached after a very considerable increase in stagnation pressure. The lower portion of the stability curve is already familiar, the existence of the upper portion has ~~only~~ been demonstrated only for the case of hydrogen by Annushkin and Sverdelov[4]. The critical diameter for hydrogen is near 1 mm making it relatively easy in terms of the amount of gas required to traverse the upper portion of the curve.

Shown on the figure at about 900 m/s and 1 mm diameter is a symbol which signifies an attempt at igniting methane from a 1 mm hole drilled in a cap installed in a high pressure manifold connected directly to a gas cylinder. By holding a propane torch some distance from the manifold, portions of the gas could be ignited, indicated by some blue flame and increased noise. As the propane flame was removed, however, all indications of flame ceased. Extrapolation of the curve in Figure 4 would indicate that considerably more pressure would be required to again enter the stable flame regime at this small exit diameter. The last point drawn on the curve at about D = 13 mm is for flow already at a Mach number of 4.

The filled circles on the figure refer to stable flames at flow rates sufficient to reach the velocity indicated at the top of the symbol. The actual gas flow rate in kg/s is given in the brackets. At D = 50.8 mm the flame did not blow off for velocities up to 800 m/s. This is well beyond the knee of the stability plot, the area where the extrapolation ought to be reasonably accurate. At 45 mm the stable behavior is repeated with one exception, i.e., the lone cross symbol among all the stable points. It is suspected, but can't be documented, that a gust of wind may have been responsible for this anomaly. This region quite near the turning point, however, may well be not so well-defined as regards exact location of the stable-unstable demarcation nor is the phenomena itself perhaps that repeatable.

At 38 mm we see both blowoff and the upper stability region. As regards the inexactness of the demarcation just discussed, observe the stable (filled circle) and blowoff (cross) coexisting at practically the same point near 500 m/s. Above this point there is an area where the flame clearly is unstable (3 crosses) and above that a region quite clearly stable (5 filled circles).

After some initial experimentation a quite definable transition-to-supercritical flow scenario emerges for flames in this region. Starting at low flow rates the gas velocity is increased which eventually leads to a lifted flame. Further increase in gas flow results in the flame height remaining practically constant, lift-off height increasing and flame luminosity decreasing while sound pitch increases to a squeal similar to a gas turbine. At this point with further increase in flow rate the ghost-like flame either blows off if the next step in flow rate is small enough or else, for larger increments in flow rate, the luminosity will begin to reappear, the sound changes to a lower frequency, higher intensity rumble followed by very big increases in flame height and luminosity with further increase in flow. Beyond getting larger no further change in flame character was noted at least to the capacity of the present gas supply.

The extrapolation of Eq. (9) in forming the upper stability curve appears to do a reasonable job in estimating where the 38 mm result might fall - there are stable flames above and below the line in more or less equal numbers. Had it been perfect, of course, it would turn more sharply and fall below the bottom most of the five filled circles. (Recall that Eq. (9) is a least-squares fit of only the blowoff points, crosses and pluses.)

The additional data at 76 and 102 mm were available from other extinguishment studies and although confirming the absence of blowoff to those indicated velocities, can not offer any substance to the validity of the shape of the derived stability curve. There is anecdotal evidence quoted by Kalghatgi[3] that the point at 10 cm can be further increased to approximately 900 m/s.

The reason the curve turns back towards smaller diameters in the supercritical regime has been described in some detail previously[3,4,10]. From Eqs. (7), (8), and (9) $\bar{U}_e$ increases monotonically with D_e for all cases. For subsonic situations $D = D_e$ and hence U_e increases monotonically with D. For supercritical flows D_e/D, via Eq. (2), rises rapidly with Mach number or U_e and hence when U_e is plotted against D it takes a smaller value of D to satisfy Eq. (9) for increasingly larger U_e.

An additional point involving the absolute value of the determined critical diameter concerns the temperature dependence of the fuel viscosity used in the Reynolds number. A difference on the order of a factor of two is involved in the final diameter determined by the calculation between a temperature dependent viscosity and that ignoring that dependence. The present result seen on Fig. 4 uses a temperature dependent absolute viscosity.

CONCLUSIONS

Sub- and supercritical methane diffusion flames have been studied regarding geometry, stability to blowoff and radiative characteristics. The data handling of both the lift-off height and flame height data in terms of convergent-divergent nozzle expansion for the choked situation establishes a valid systematic method of analysis, i.e., making contact with laboratory scale results. Deviation from isentropic flow for large underexpanded flows has been documented. The stability of large flames has been demonstrated for methane and confirms the approach of Kalghatgi[3] and Annushkin and Sverdlov[4] to prediction. These phenomena offer combustion specialists new opportunity for modeling and characterization. For example, in premixed flame stretch extinction studies the boundary velocity gradient, $U_e/\frac{1}{2}D$, is seen to be of similar order as is observed in these studies[12].

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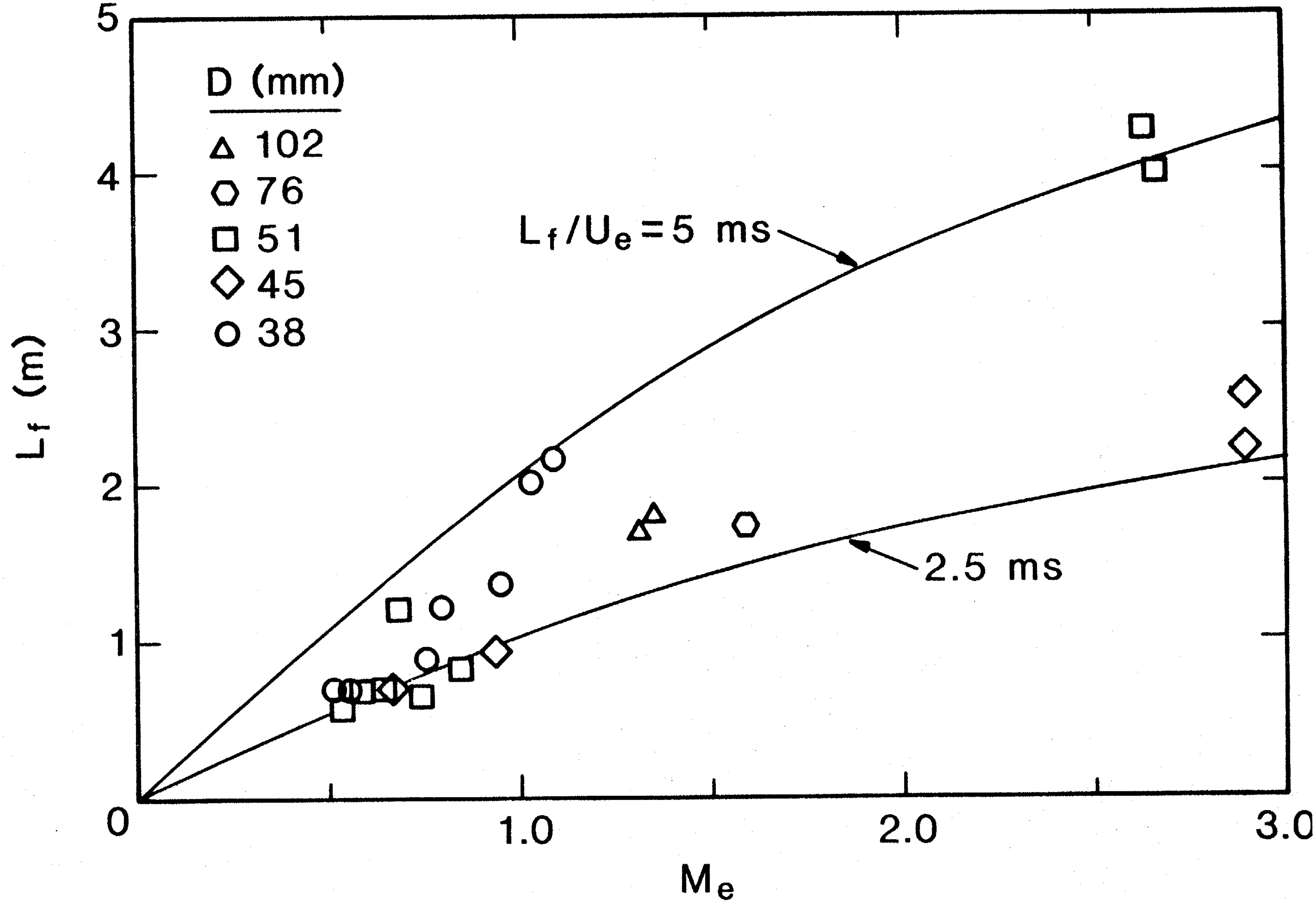
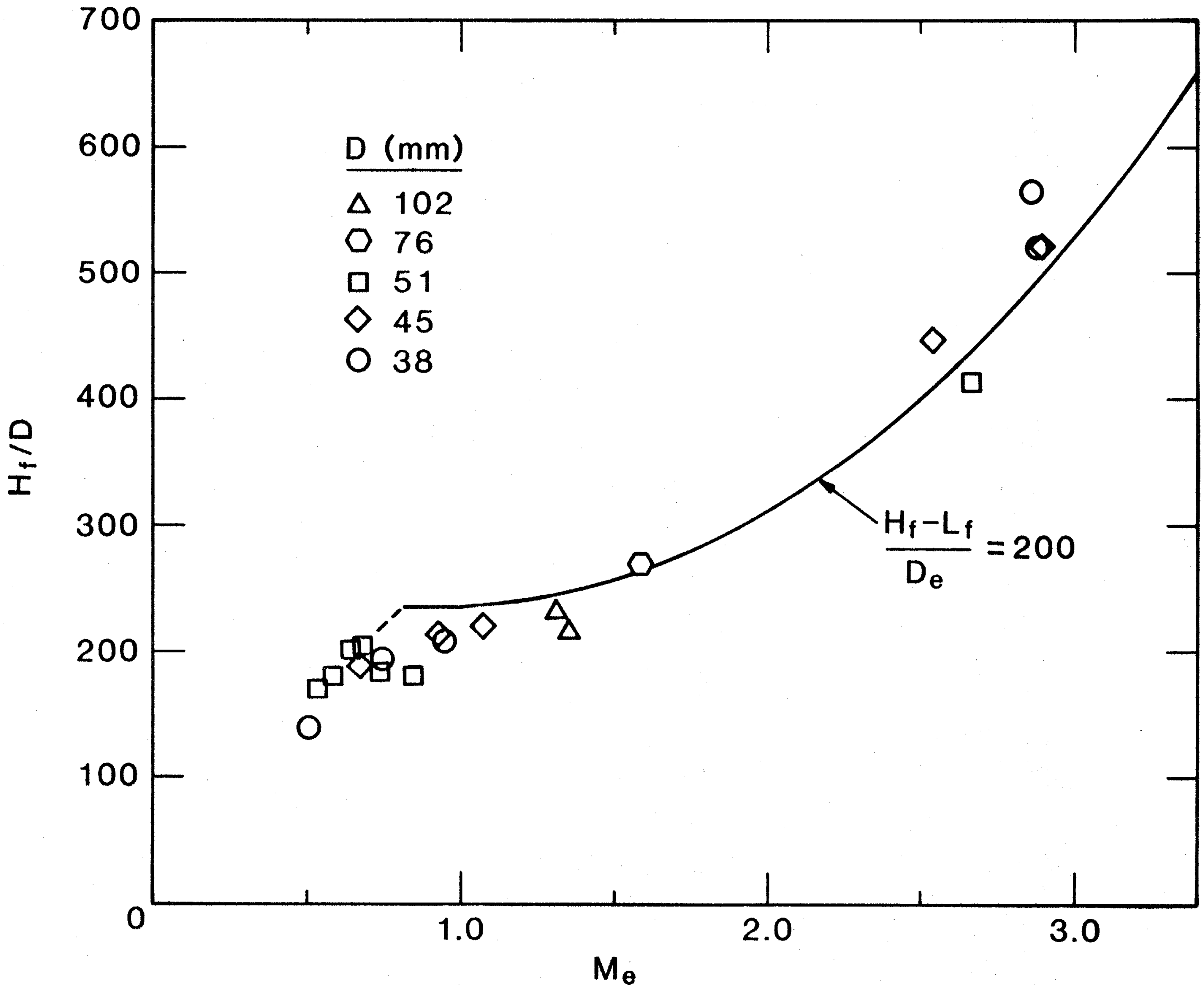
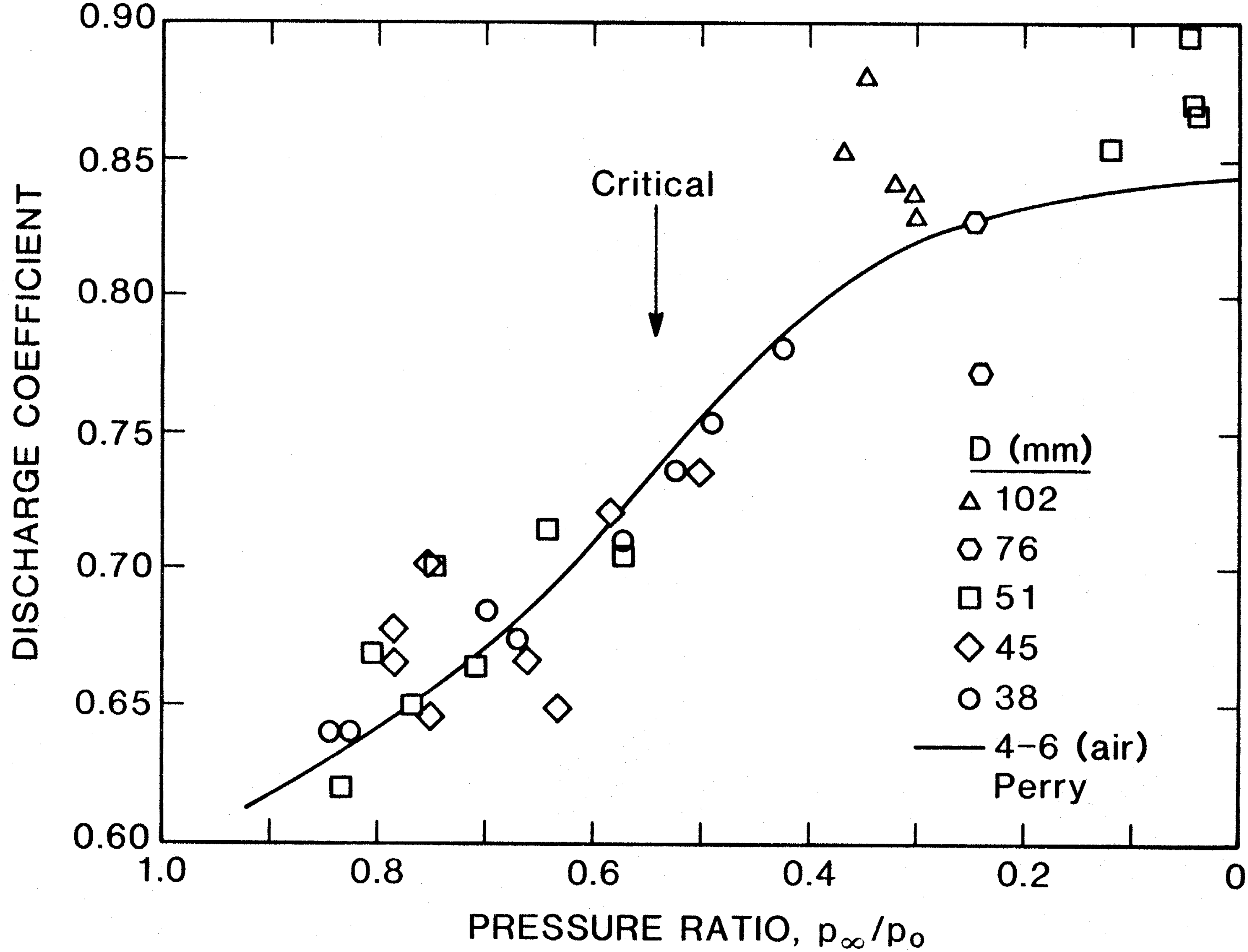
LIST OF FIGURES



D (mm)
102
76
51
45
38
$L_f/U_e = 5$ ms
2.5 ms
L_f (m)
M_e
0
1
2
3
4
5
1.0
2.0
3.0



D (mm)
102
76
51
45
38
$\frac{H_f - L_f}{D_e} = 200$
H_f/D
M_e
0
100
200
300
400
500
600
700
1.0
2.0
3.0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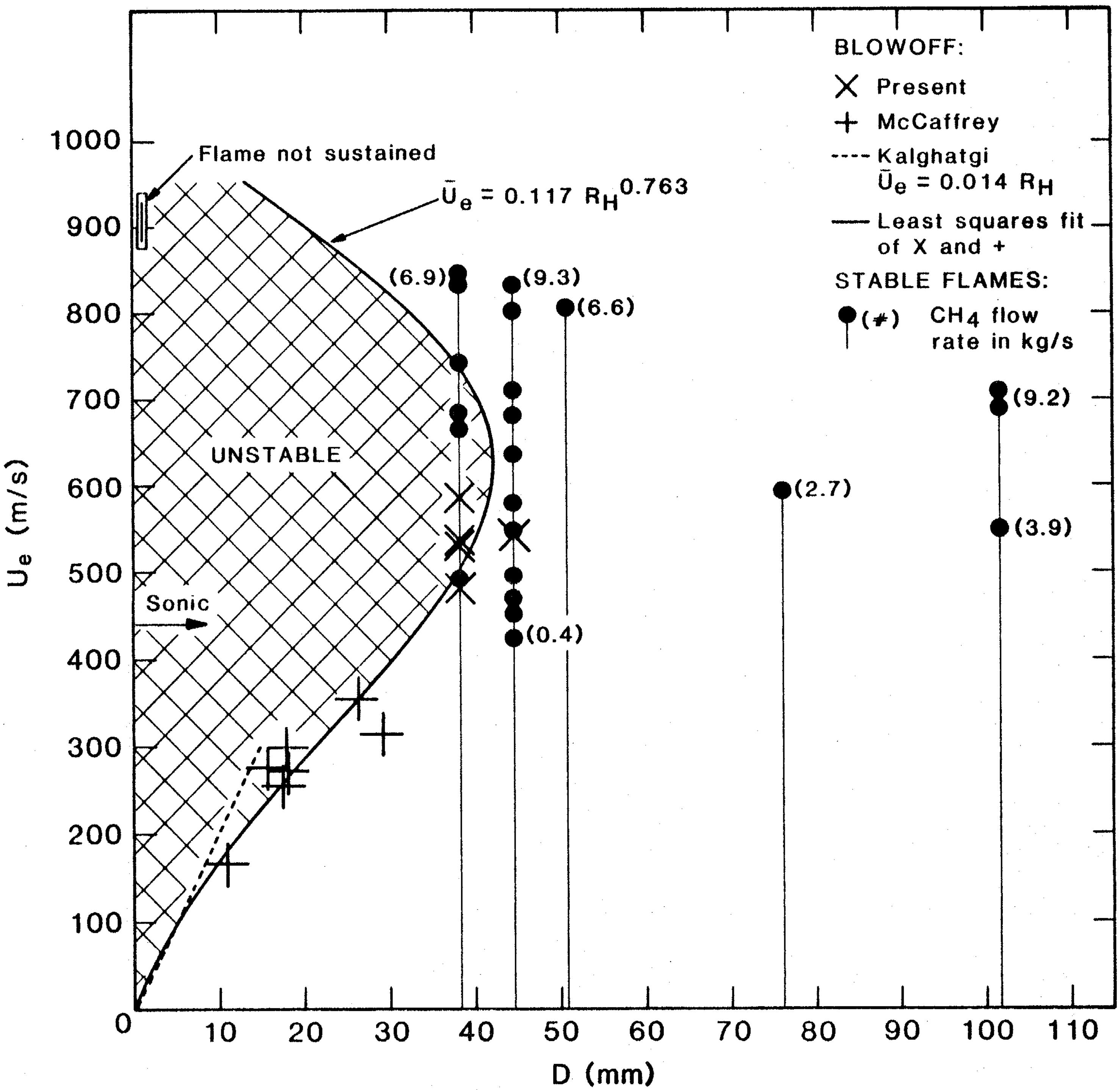
0.85
0.80
0.75
0.70
0.65
0.60
DISCHARGE COEFFICIENT
Critical
D (mm)
102
76
51
45
38
4-6 (air)
Perry
1.0
0.8
0.6
0.4
0.2
0
PRESSURE RATIO, p_∞/p_o



BLOWOFF:
Present
McCaffrey
Kalghatgi
Ūe = 0.014 RH
Least squares fit of X and +
STABLE FLAMES:
(#) CH4 flow rate in kg/s
Flame not sustained
Ūe = 0.117 RH0.763
UNSTABLE
Sonic
(6.9)
(9.3)
(6.6)
(0.4)
(2.7)
(9.2)
(3.9)
Ue (m/s)
D (mm)
0
100
200
300
400
500
600
700
800
900
1000
10
20
30
40
50
60
70
80
90
100
110