EXPLAINING THE "THREE INCH RULE": WHY MODEL FLARES DON'T MATCH FULL-SCALE

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ABSTRACT

It was Pohl and co-workers who discovered the so-called "Three Inch Rule" in their work on flares in the 1980s. They found that model flares with pipe diameter less than three inches do not have the same Combustion Efficiency (CE) and stability behaviour as full-scale flares, at least when wind is negligible. Later researchers, including the author, used model flares in wind tunnels to investigate the effects of wind on CE. These studies also found a Three Inch Rule despite the very different flow conditions.

This paper uses the published flaring data to unravel the mechanisms behind the Three Inch Rule. The flow and combustion regimes are delineated in terms of the relevant dimensionless parameters. The inadequacy of model flares smaller than 3 inches is given a theoretical basis. This result is significant for regulators of air emissions from flares, who should be wary of accepting evidence from small model flares in drafting new regulations and should revisit regulations based on those results.

INTRODUCTION

Flares are an essential safety technology for the clean and economical disposal of combustible waste gases. They have been operating in refineries, chemical plants, steel mills, and other industries for over fifty years. There have been improvement of the technology and periods of intense scientific research into the factors affecting flare performance and quantifying the emissions from flares. For a variety of reasons, model flares have been used in scientific investigations although the ability to study full-scale flares has advanced. However, the question of the range of validity of the pilot-scale results for full-scale operation must be addressed. Simple non-reacting flows, like an incompressible fluid in a pipe, admit a good understanding of flow regimes and scaling. Reacting flows are much more difficult to scale. Open combusting flows like flares are perhaps the most difficult.

Generally, elevated refinery flares are larger than 0.5 m in diameter and have exit gas momentum much greater than most crosswinds. Production flares, at least in western Canada, are between 10 cm and 30 cm and frequently experience strong winds (average wind speed approximately 20 km/h or 5.5 m/s).

Experiments have studied vertical flares with negligible wind effect and the effect of strong winds. It has been shown in both circumstances, with and without wind effect, there is a minimum flare diameter around 7.5 cm (3 inches) below which the results at the pilot-scale do not match full-scale. The evidence is reviewed here. Analysis of the phenomena using the appropriate dimensionless numbers is used to explain this lower limit on flare size. This is important for both operators and regulators of flares, as well as those investigators who want their results to be relevant for operating flares.

THE EMPIRICAL EVIDENCE

Jetting Flares

The years from 1984 through 1986 saw published three reports on the work performed at Energy and Environmental Research Corporation (EER) for the US EPA on flare efficiency (Pohl et al.

[1984], Pohl and Solberg [1985, 1986]). The third report on the series, Pohl and Soelberg [1986] treated H_2S and the effect of pilots and used 7.6 cm and 15.2 cm (3" and 6") simple pipe flares.

Pohl et al. [1984] reported tests flaring propane and nitrogen mixtures, with 7.6 cm, 15.2 cm, 30.5 cm (3", 6" and 12") diameter simple pipes, and three 30.5 cm (12") diameter commercial flare tips. Both the rake and hood measurement techniques were used. Steam-assist was used in some of the tests, which will not be considered here. Wind was deliberately excluded from the testing.

They determined stability based on emissions of unburned material, noting that flames near the stability limit are very sensitive to perturbations and when perturbed can produce high emissions of unburned material.

Combustion efficiency was better than 98% when the heat content of the propane/nitrogen mixture was above 1.1 times the minimum heat content determined from the stability curve. Near the stability limit the combustion efficiency can degrade significantly, to the point of being random. This degraded efficiency is the result of the sensitivity of the flame to perturbations. This is shown in Figure 1 for the tests with simple pipes (3", 6" and 12" diameters).

Based on these results, they related the heating value to the exit velocity for the unstable flares and identified a region for instability for these simple pipes and three 30.5 cm (12") diameter commercial flare tips. This region for instability is shown in Figure 2, together with the data points from Figure 1.

Pohl and Soelberg [1985] continued the work to look at flare design and gas composition. They selected several compounds that are particularly difficult to combust or have a strong propensity to smoke. They used the hood sampling technique for small flames and a tracer (SO_2) for large flames, to control the material balance. They found that the correlation developed in their first report was applicable to different gas mixtures and different flare tip designs. While Pohl et al. [1984] showed that 7.6 cm (3") pipes produce similar flames to larger pipes, in the second report they concluded that flames produced in pipes less than 6.3 cm (2.5") diameter are not similar to the larger sizes. This report includes results from the Flare Screening Facility where a very small pipe (either 0.2 cm or 0.3 cm (1/16" or 1/8")) was used. They used this equipment for preliminary testing to expedite the pilot-scale work. They found that the maximum stable exit velocity and even the relative ranking of the gases using the small pipe did not correspond to the larger scale

(3” and larger) results. This is shown in Figure 2 for the 2.5 cm (1”) simple pipe, with the instability data from Figure 1 and the instability region for larger flares. The instability data for the 1-inch pipe falls outside the region for the larger flares. Instability data for pipes smaller than 1-inch are further away from the instability region for full-scale flares. This places an important lower limit on pipe size that can be used for jetting flare studies and subsequent studies (e.g., EER [1997]) used 7.6 cm (3”) pipes or larger.

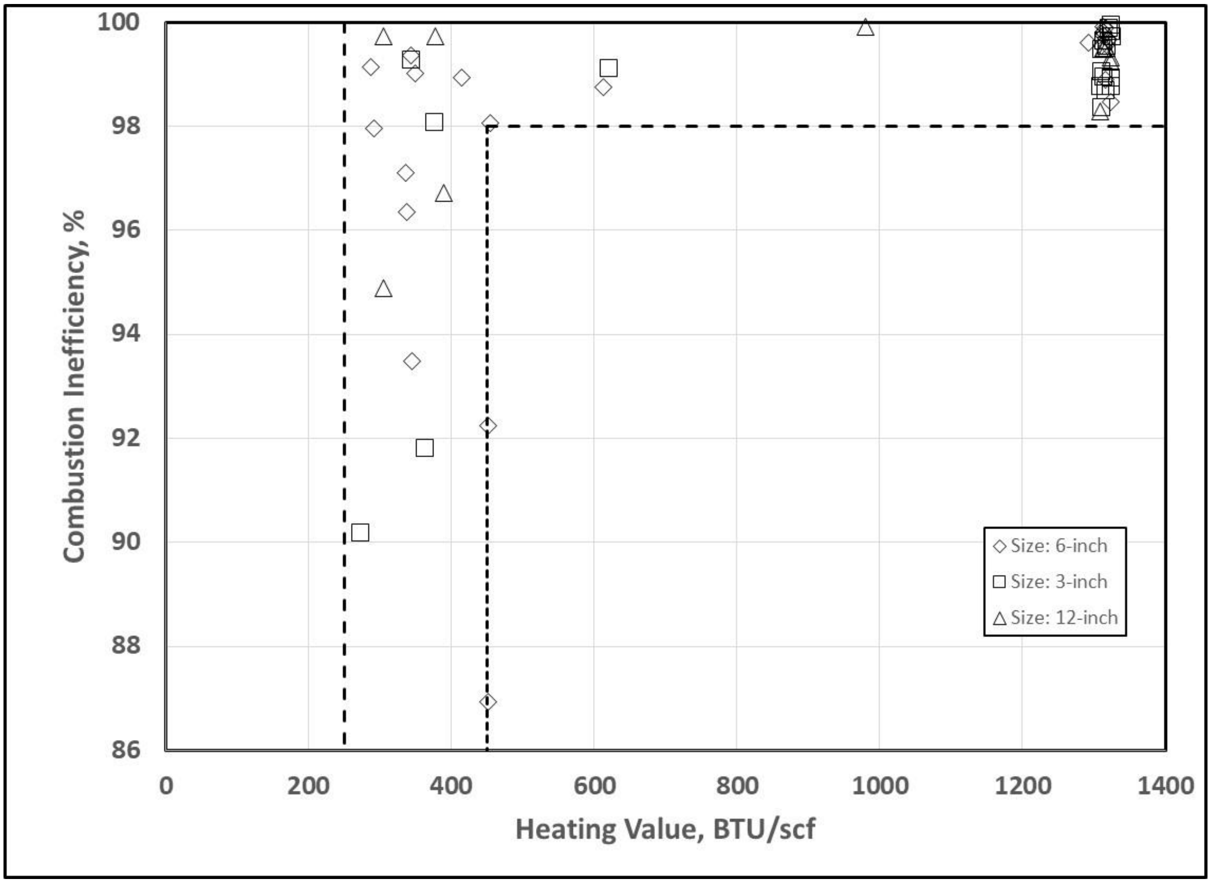

Figure 1 – Diagram illustrating the instability at low heating value for 7.6cm, 15.2cm, 30.5cm (3”, 6” and 12”) diameter simple pipes from Pohl et al. [1984].

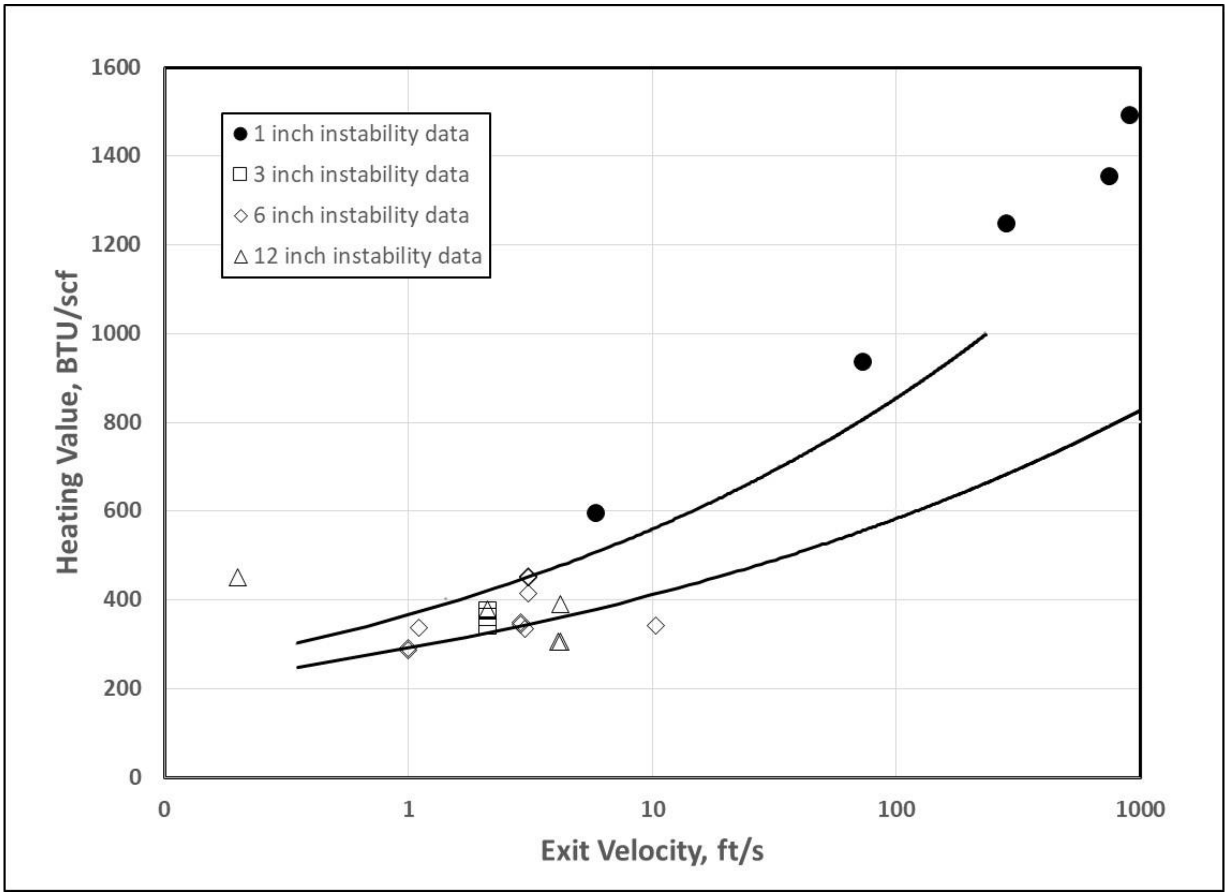

Figure 2 - Instability Map for 2.5 cm (1") pipe compared to 7.6 cm (3") to 30.5 cm (12") pipes, Pohl et al. [1984, 1985]

Wind-blown Flares

The University of Alberta started a program in the late 1990s to investigate the efficiency of solution gas flares in Western Canada, and particularly the effect of wind. A particular characteristic of these flares is the low momentum of the flare gas, with exit velocity of the solution gas less than the average wind speed of 4m/s to 7 m/s. These conditions can produce the wake-stabilized regime identified by Kalghatgi [1981]. They developed an experimental methodology using a closed-loop wind tunnel (Bourguignon et al. [1999]). Simple pipe flares with diameter 0.6 cm, 1.3 cm, and 2.5 cm (0.25", 0.5" and 1") were used in this facility. The maximum crosswind speed was 14 m/s (31 mph). Commercial natural gas and propane were fired, as was ethane. Tests were done with carbon dioxide as an inert diluent. The subsequent series of papers chronicle the progress of the work on this facility at the University of Alberta. The main results are contained in the reports Kostiuk et al. [2000a,b; 2004]. It is important to note that these tests were aimed at solution gas flares, which are very different from the large industrial flares treated by Pohl and co-workers. These differences include simple tip design and smaller diameter, no steam or air assist, relatively simple flare gas composition, and CO_2 as the primary diluent instead of N_2.

Johnson et al. [1998; 1999a,b; 2000], and Johnson and Kostiuk [1999; 2000] showed that crosswind speed has a strong negative effect on combustion efficiency and verified the existence of the "wake stabilized" regime found by Kalghatgi (1981), which is quite different from the strong vertical flame studied by earlier investigators. They used a dimensionless parameter based on the model of a buoyant plume from a stack

$$BP = \frac{U_w}{\left(gD_pU_f\right)^{\frac{1}{3}}}$$

and correlated the measured combustion inefficiency with an exponential curve

$$\mathrm{CI} = \frac{ae^{bBP}}{(\mathrm{LHV}_m)^3}$$

where *a* and *b* are parameters fit to the experimental data, different for "methane-like" or "propane-like" gas. No rule was given for deciding which to apply, although ethane was considered "propane-like".

However, a later paper from the group (Howell et al. [2003]) reported a series of experiments in a much larger single-pass wind-tunnel with larger pipes to test the scale-up validity of the correlation. The pipes tested were 2.5 cm, 5.1 cm, and 10.2 cm (1", 2" and 4") diameter. A rake system was used to sample the combustion gases. They suggested a better fit to the experimental data is obtained with a square-root dependence on pipe diameter even though this would no longer be dimensionless. The actual problem is that the results from the smaller pipes do not scale-up.

We have replotted the data from Howell et al. [2003] in Figure 3 with a log-linear scale to better distinguish the effect of pipe size. Errors bands of ±100% for the University of Alberta correlation are placed to show the magnitude of the deviation from the correlation for the inefficiency data for larger pipes. The combustion inefficiency with 2.5 cm (1") pipe lies broadly within the 100%

error bands. The combustion inefficiency for the 10.2 cm (4”) pipe is uniformly less than 1% (greater than 99% combustion efficiency) in these tests and deviates significantly and systematically from the 1” pipe data and the correlation developed with smaller pipes. Certainly the University of Alberta correlation of small pipe data does not scale-up to the larger flares.

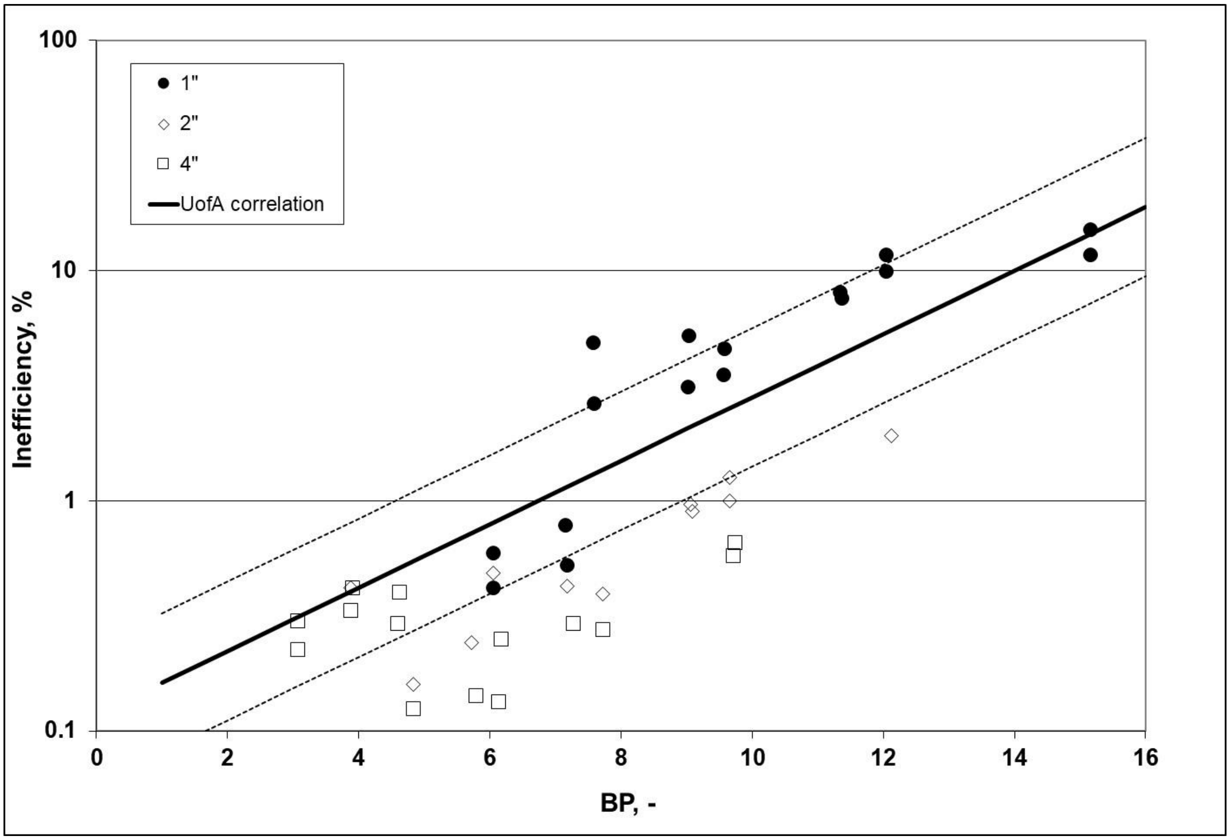

Figure 3 - The data from Howell et al. (2003) plotting the combustion inefficiency (CI) against the Buoyant Plume number BP, with ±100% error bands on equation (3). Log-linear plot allows the data for the different pipe sizes to be easily distinguished.

A program of investigation with similar scope was started at the CanmetENERGY Flaring Test Facility (FTF) (Gogolek et al. [2001]). A single pass wind tunnel was fabricated for this work. Natural gas and propane were fired, singly and in mixtures. Nitrogen and carbon dioxide were used as inert diluents. Pipe sizes from 2.5 cm to 15.2 cm (1” to 6”) were used. Different configurations of wind shroud were tested, as was the effect of cross-wind turbulence, with the objective of understanding the performance of simple solution gas flares.

A different dimensionless parameter was constructed to combine both the effect of flare gas composition and crosswind speed. It is the ratio of the power of the cross-wind to the power of combustion of the flare gas. The cube root of this ratio was called the Power Factor, PF, and takes the form

$$PF = \left(\frac{\rho_a U_w^3 D_p^2}{\dot{m}_f LHV_m} \right)^{1/3}$$

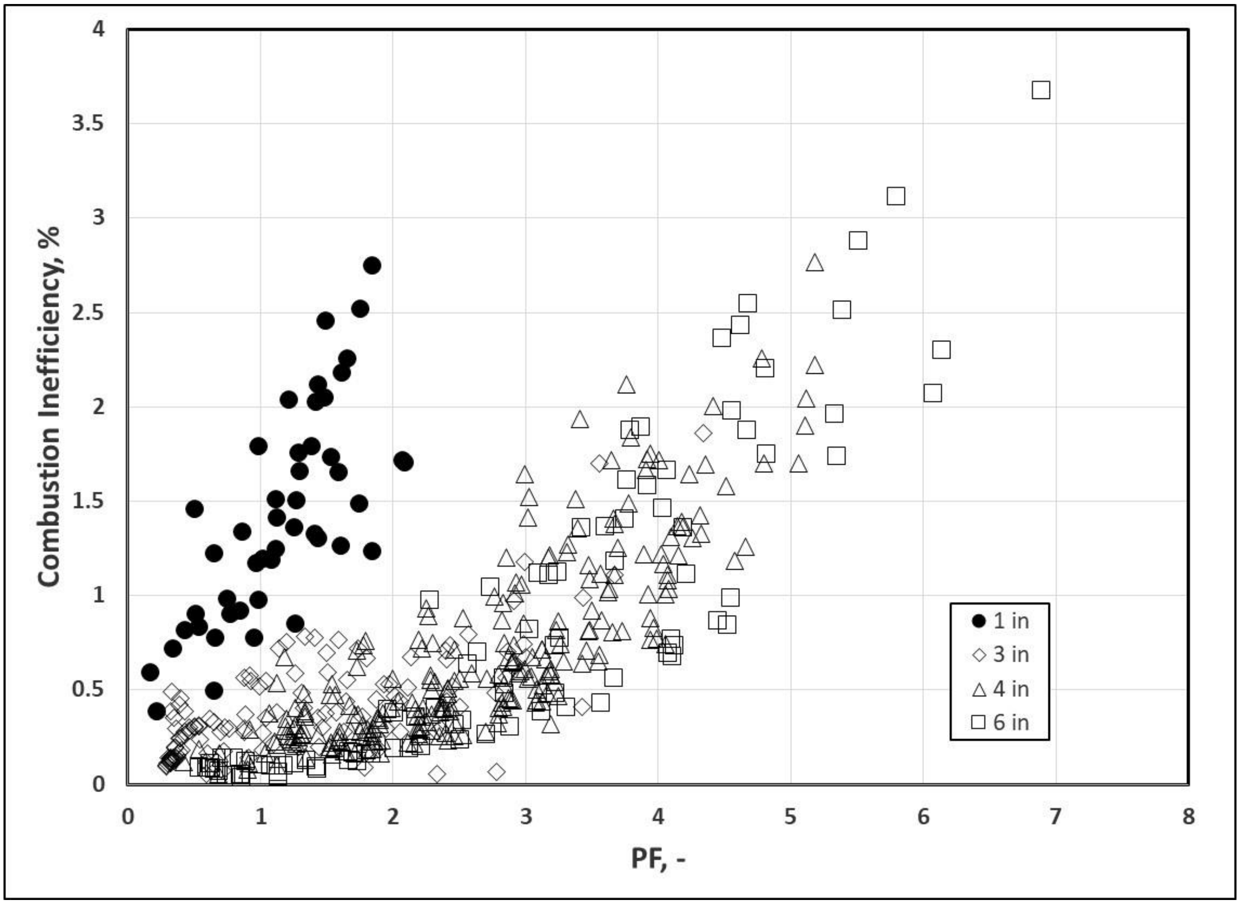

Figure 4 - Natural gas flaring combustion inefficiency data from the CanmetENERGY FTF for pipe flares of 2.5 cm, 7.6 cm, 10 cm, and 15.2 cm (1", 3", 4" and 6") diameter against the Power Factor, PF.

The data from CanmetENERGY FTF also shows the divergence between the 2.5 cm (1”) and simple pipes 7.6 cm, 10 cm, and 15.2 cm (3”, 4” and 6”) diameter. The combustion inefficiency (CI) data for natural gas flaring with these four pipe sizes are shown in Figure 4 plotted against the PF. These data show clearly that 2.5 cm (1”) model flares have higher inefficiency than the full-scale flares (7.6 cm and larger), which are grouped together, and the that minimum scalable pipe diameter is approximately 7.6 cm (3”), the same as found for the jetting regime.

FLUID DYNAMICAL REGIMES

The physical design characteristics and flow regime of an elevated flare determine the mixing behaviour between the air and flare gas, which is important for combustion. Here we are only considering the simple pipe flare, which is typical of those used in published scientific studies.

The mixing in a flare flame, with the possible presence of a crosswind, will depend on the air and fuel properties, average speeds, and pipe size. From these flow variables one can form two dimensionless parameters representing the relative strength of the momentum fluxes. One is the Froude Number

$$Fr = \frac{\rho_f U_f^2}{\left(\rho_a - \rho_p\right) g D_p}$$

the ratio of the jet strength to the buoyancy of the burned gases. When Fr is large the jet flame is momentum driven while buoyancy driven flames have Fr less than 1. The other ratio is the momentum flux ratio

$$R = \frac{\rho_f U_f^2}{\rho_a U_w^2}$$

which gives the relative momentum strength of the fuel jet to the crosswind.

With a strong wind that produces the wake-stabilized regime the burning flare gas is pulled into the wake of the flare stack. The literature on the effects of wind on smokestack design and performance can provide some guidance. Downwash is the phenomenon where the plume from the stack is pulled into the wake of the stack and the pollutants in the plume more easily reach ground level. This is similar to the wake-stabilized flame, but without combustion. Downwash has been shown to occur for a momentum flux ratio of $R < 2.5$ (Overcamp [2001] and Tatom [1986]) with the stack Reynolds number in the critical regime ($Re_w > 300{,}000$), that is for large diameter stacks and moderate to high winds. This indicates that the onset of wake-stabilized combustion for elevated flares could occur for momentum flux ratios greater than unity.

The flames produced during the flaring tests at the Flare Test Facility were classified according to the following five categories:

- *Strong Jet* – Flow dominated by inertia of flare gas leaving the flare tip.
- *Jet dominated* – Flow dominated by the jet momentum near the flare tip but the crosswind bends the flame over in an arc.
- *Transition* – The flame rises a few diameters above the tip then bends sharply.
- *Crossflow dominated* – The flame rises about a diameter above the tip but the main body of the flame is downwind of the flare.
- *Downwash* – The flame is anchored in the wake of the flare and attached to the pipe.

These tests had pipe sizes of 1, 2-, 3-, 4-, and 6-inch diameter, firing natural gas, propane or a 70% natural gas and 30% propane mixture. Some tests had a turbulence generating grid in place. These observations are collected in Figure 4, with the Froude Number and Momentum Flux Ratio as the axes. The boundaries for the five regimes are:

- *Strong Jet* – $R > 10$.
- *Jet dominated* – $3 < R < 10$.
- *Transition* – $1.6 < R < 3$.
- *Crossflow dominated* – $0.1 < R < 1.6$.
- *Downwash* – $R < 0.1$.

Note that the Transition regime straddles the boundary for the onset of downwash for smokestacks noted above.

The Buoyant Flame regime does not appear in Figure 4 because the experiments were performed in a wind tunnel. The low Froude Number runs had wind momentum greater than the fuel momentum.

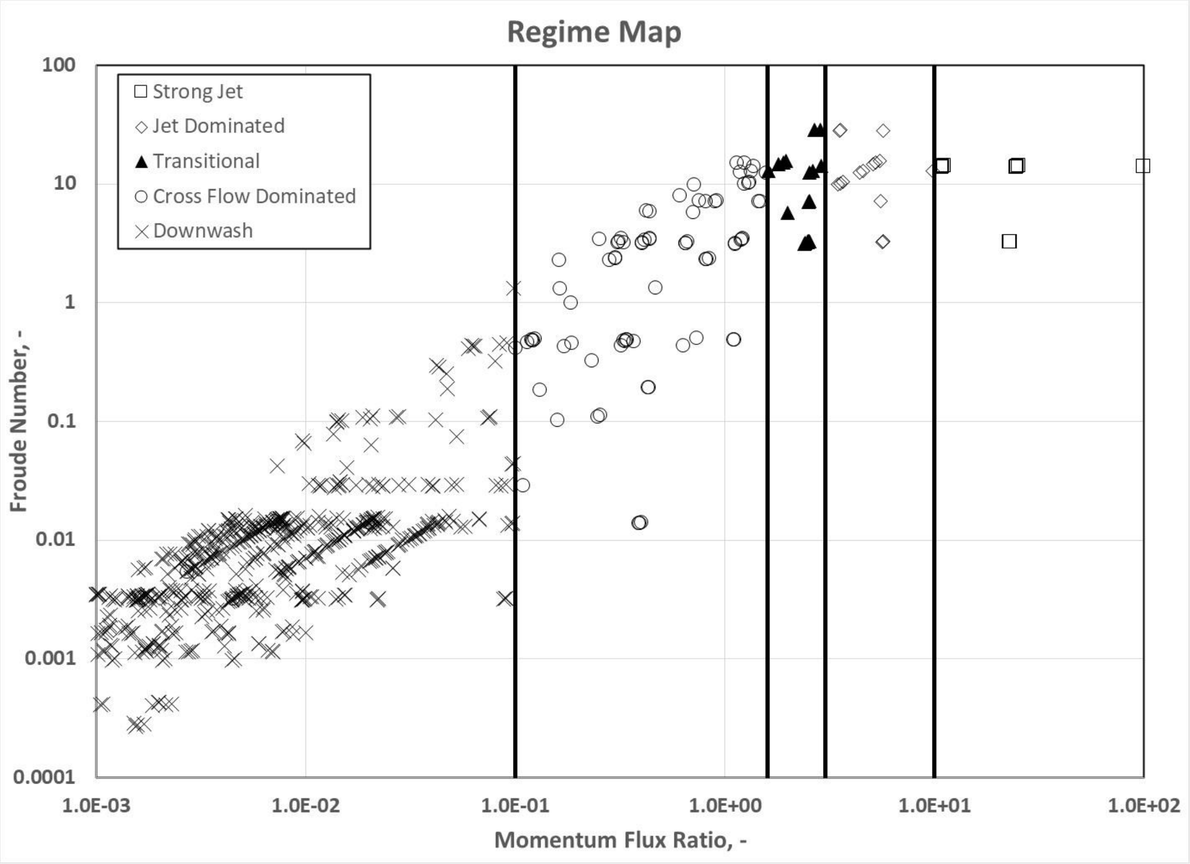

Figure 4 - Regime map for flaring with wind based on the momentum flux ratio.

DISCUSSION OF JETTING LIMIT

The stability limit is a relationship between the heating value of the gas and the exit velocity, shown in Figure 2 above. Furthermore, pipes smaller than 7.5 cm (3 in.) do not have the same stability limit as larger pipes so that this is the limit for model flares to be relevant to the full-scale in this combustion mode.

The instability diagram Figure 2 can be made dimensionless. A dimensionless heat content is formed by noting that the lower heating value on a mass basis has the units of L^2T^{-2}.

$$H^* = \frac{LHV_m}{gD_p}$$

The dimensionless velocity U^* is given by

$$U^* = \frac{U_f}{(\nu_f g)^{1/3}}$$

The data from Pohl et al. [1984] in the instability map in Figure 2 are converted to the dimensionless parameters H^* and U^*, including the boundaries of the stability region in Figure 3, and presented in Figure 5. The instability data now show more clearly the divergence of the 2.5 cm (1”) pipe data from the larger flares, which are grouped more closely together than for the dimensional plot.

A tidier graph, comparing Figures 2 and 5, is nice but does it help explain anything? Note that the instability points from Figure 2 are colinear in Figure 5 for the 3-, 6- and 12-inch pipes. This suggests that the dimensionless heat content captures something significant. The scaling factor in the denominator is gD_p and this is a measure of the buoyancy effect and flame size. This suggests that for pipe flares 7.5 cm (3”) in diameter and larger the flame is large enough that buoyancy or some other mechanism helps to stabilize it.

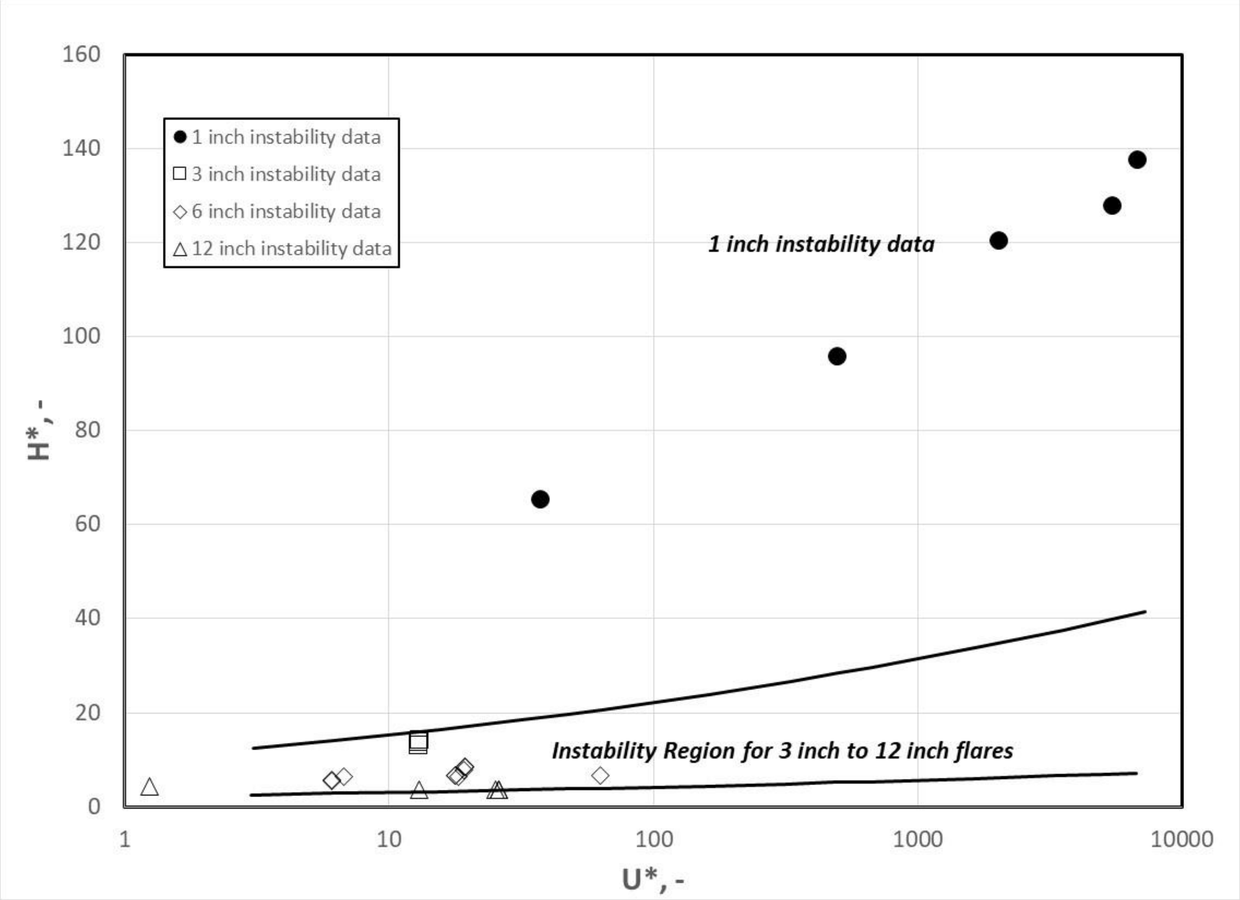

Figure 5 - Dimensionless instability map for 7.6 cm to 30.5 cm (3” to 12”) diameter pipe flares and 2.5 cm (1”) pipe instability data from Pohl et al. [1984].

DISCUSSION OF WAKE-STABILIZED LIMIT

The wake-stabilized flare is dominated by the crosswind, with the flame drawn into the low-pressure wake of the flare pipe. This stabilizes the flame but also introduces sources of inefficiency that increase with increased wind speed. This is a continuous process, unlike the relatively sharp onset of instability for the jetting regime. The published experimental data examined above shows unambiguously that a Three Inch Rule applies.

The natural place to look for an explanation is the regimes for crossflow on stacks: laminar, subcritical, critical and supercritical. If there is crossing of regime boundaries as the pipe size increases, then that would be a likely explanation. However, the crosswind speed in the studies ranged from 3.6 km/h to 45 km/h (1 m/s to 12.5 m/s) giving crosswind Reynolds numbers from

2400 to 110,000 for the pipes from 2.5 cm to 15.2 cm (1” to 6”) diameter. These crosswind Reynolds numbers are well within the subcritical regime. The dynamic force coefficient passes through a maximum at Reynolds number around 70,000. However, both 2.5 cm (1”) and 7.6 cm (3”) pipes have crosswind Reynolds numbers below 60,000 for the range of crosswind speed used in these experiments. Therefore, neither crossflow regime transition nor the dynamic force maximum explain the Three Inch Rule in the wake-stabilized regime.

The range of fuel exit velocity for a 2.5 cm (1”) pipe was from 7.3 m/s to 22.4 m/s while for the 7.6 cm (3”) pipe the exit velocity ranged from 0.6 m/s to 2.6 m/s to give the same range of fuel input. The momentum flux ratio *R* for the 7.6 cm (1”) experiments ranged from 0.24 to 100, or from crossflow dominated to strong jet, according to the Regime Map in Figure 4. Observations of the flow regime as Strong Jet, Jet Dominated, Transitional or Crossflow Dominated were recorded for the 7.6 cm (1”) pipe tests at the CanmetENERGY FTF. Figure 6 shows the regions within the experimental conditions for each regime for the 7.6 cm (1”) pipe, with the experimental points from the CanmetENERGY FTF. Out of the 47 runs, only half the runs (24) were in the wake-stabilized regime and almost a quarter (11) were in the jetting regime. And it is established that the Three Inch Rule applies in the jetting regime. For pipes smaller than 2.5 cm (1”), such as used at the University of Alberta, the number of run conditions in the jetting regime will be much larger. However, for 7.6 cm (3”) pipes the exit velocity for the same heat input is nine times smaller and crossflow dominated and downwash regimes cover almost the whole of the experimental matrix. The corresponding range of the momentum ratio for the 7.6 cm (3”) pipe was 0.003 to 3, so none of those tests are in the jetting regime.

The tests at the University of Alberta and at CanmetENERGY FTF were aimed at understanding the behavior of solution gas flares. These flares will operate in the jetting and wake-stabilized regimes as the wind speed varies. However, it has been shown that pipes smaller than 7.6 cm (3”) do not scale for the jetting regime. Using 2.5 cm (1”) model flares will not scale for at least part of operating conditions. If the problem was only that of the jetting regime it could be handled by putting restrictions on the heat content of the flare gas since that is the cause of inefficiency in that regime. The scaling problem for the wind-driven inefficiency is due to the mismatch between the regime transition and the correlation. The regimes boundaries are determined by the momentum

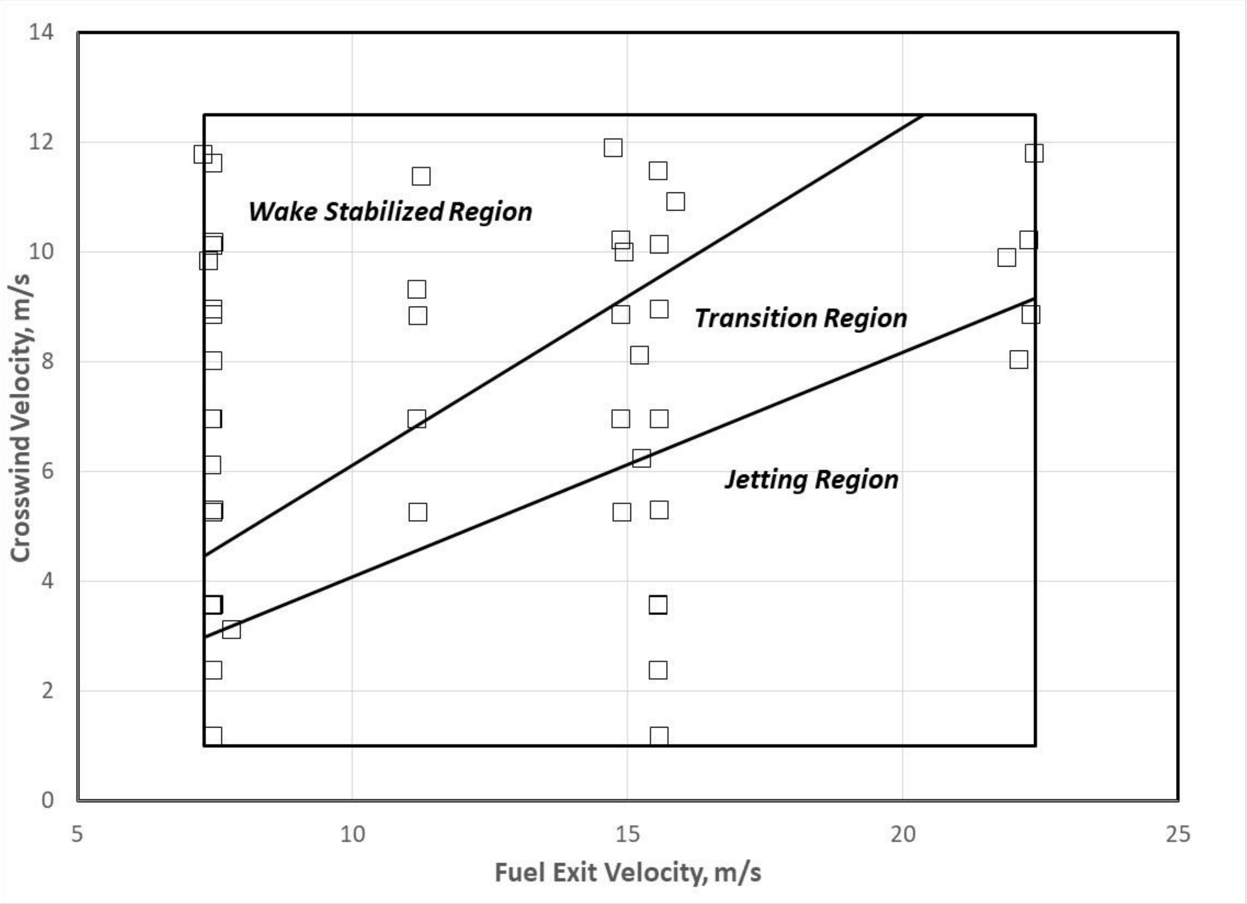

Figure 6 - Map of the observed regimes for a 1 inch pipe, with the experimental conditions performed on the FTF of CanmetENERGY.

flux ratio. The inefficiency due to wind is correlated with a parameter (*BP* or *PF*) that has no relation to the momentum flux ratio. The problem is not that there is a Three Inch Rule for flares in a crosswind but that the limitations of experiments in wind tunnels confounded regime transitions with pipe size. In other words, the experiments with larger pipes were all in the crosswind dominated regime while the smaller pipes spanned multiple regimes.

CONCLUSION

The Three Inch Rule has been well established experimentally for the jetting regime since the work of Pohl and co-workers in the early 1980s. All subsequent work of any significance on jetting flares was done respecting the Three Inch Rule. However, work started in the late 1990s on the effect of wind did use smaller model flares and it was found that the Three Inch Rule also applied to this work, that the 2.5 cm (1”) model flare results do not scale up to the larger sizes. This experimental evidence is represented here.

The original work in the jetting regime showed that flare inefficiency is manifested as instability when the heating value of the flare gas approaches a critical value. This stability limit was expressed as a relationship between heating value and flare gas exit velocity. The data were analyzed here and presented with a new dimensionless heat content parameter that clearly shows the discrepancy between 2.5 cm (1”) model flares and those 7.6 cm (3”) diameter and larger.

The results for 2.5 cm (1”) and smaller model flares with a crosswind are shown to be in the transition or jetting regimes for many of the experimental conditions. Since the model flares 7.6 cm (3”) in diameter and larger are in the wake-stabilized regime for all the experimental conditions, the small pipe model flares cannot match the results of the larger flares because these are operating in different regimes. The Regime Map in Figure 4 shows the boundaries between regimes for the effect of crosswind and these boundaries are determined by the momentum flux ratio.

The Three Inch Rule has more than academic interest. The 2.5 cm (1”) model flare results over-estimates the inefficiency in wind affected flares and over-estimates the heat content for the stability limit in the jetting regime. In the wind affected case, this over-reports the emissions of greenhouse gases, particularly methane, for solution gas flares. In the jetting case this would require supplemental fuel when none is needed, adding cost and GHG emissions.

REFERENCES

Bourguignon, E., Johnson, M.R., and Kostiuk, L.W. [1999] "The use of a closed-loop wind tunnel for measuring the combustion efficiency of flames in a cross flow." Combustion and Flame, **119,** pp.319-334.

Gogolek, P., Hayden, A.C.S., and Madrali, S. [2001] "Performance and Speciation of Solution Gas Flares Tested in the CANMET Flare Test Facility - Final Report." CETC report to PTAC.

Howell, L.W., Poudenx, P.D., Johnson, M.R., Wilson, D.J. and Kostiuk, L.W. [2003]. “Flare Stack Diameter Scaling.” Combustion Canada Conference 2003, Calgary, AB.

Johnson, M.R., and Kostiuk, L.W. [2000] "Efficiencies of Low-Momentum Jet Diffusion Flames in Crosswinds." Combustion and Flame, **123**, pp. 189-200.

Johnson, M.R., Wilson, D.J., Kostiuk, L.W. [2000] “A Fuel Stripping Mechanism for Low-momentum Jet Diffusion Flames in a Crossflow. Combustion Science and Technology, **169**, pp. 155-174.

Kalghatgi, G.T. [1981] “Blow-Out Stability of Gaseous Jet Diffusion Flames. Part II: Effect of Cross Wind”, Combustion Science and Technology, **26**, pp. 241-244.

Kostiuk, L.W., Johnson, M.R., and Prybysh, R.A. [2000a] "Recent Research on the Emission from Continuous Flares." Combustion and Environment Group, Department of Mechanical Engineering, University of Alberta.

Kostiuk, L.W., Majeski, A.J., Poudenx, P., Johnson, M.R., Wilson, D.J. [2000a] “Scaling of Wake-Stabilized Jet Diffusion Flames in a Transverse Air Stream”, Proceedings of the Combustion Institute, **28**, pp. 553-559.

Kostiuk, L.W., Johnson, M.R., and Thomas, G. [2004] "University of Alberta Flare Research Project Final Report November 1996 – September 2004" Combustion and Environment Group, Department of Mechanical Engineering, University of Alberta.

Overcamp, T.J. [2001] “A review of the conditions leading to downwash in physical modeling experiments.” Atmospheric Environment, **35**, pp. 3503-3508.

Pohl, J.H., Payne, R., and Lee, J. [1984] "Evaluation of the Efficiency of Industrial Flares: Test Results." EPA-600 /2-84-095.

Pohl, J.H., and Soelberg, N.R. [1985] "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition”. EPA-600/2-85-106.

Pohl, J.H., and Soelberg, N.R. [1986] "Evaluation of the Efficiency of Industrial Flares: H_2S Gas Mixtures and Pilot Assisted Flares". EPA-600/2-85-106.

Tatom, F.B. [1986] “Predictions of stack plume downwash.” Journal of Fluids Engineering, **108**, pp 379-382.

NOMENCLATURE

ν_a	Kinematic viscosity of air (m^2/s)
ν_f	Kinematic viscosity of fuel gas (m^2/s)
ρ_a	Density of air, (kg/m^3)
ρ_f	Density of fuel gas, (kg/m^3)
A_p	Open area of flare pipe (m^2)
BP	Buoyant Plume parameter (dimensionless).
CE	Combustion Efficiency (%).
CI	Combustion Inefficiency, = 100% - CE (%).
D_p	Diameter of flare pipe (m).
Fr	Froude number (dimensionless).
FTF	Flare Test Facility
g	Acceleration due to gravity (m/s^2).
LHV_m	Lower Heating Value, mass basis (MJ/kg).
$\dot{m}_f$	Mass flow of fuel gas (kg/s)
PF	Power Factor (dimensionless).
R	Momentum flux ratio of jet to crosswind (dimensionless).
Re	Reynolds number (dimensionless).
Re_p	Reynolds number for flow inside a pipe (dimensionless).
Re_w	Reynolds number for pipe in crosswind (dimensionless).
U_f	Exit speed of fuel gas (m/s).
U_w	Mean crosswind speed (m/s).
U^*	Dimensionless exit velocity (dimensionless).