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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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STEAM TURBINES OF GREAT OUTPUT

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III НАУЧНАЯ КОНФЕРЕНЦИЯ

на тему

ПАРОВЫЕ ТУРБИНЫ БОЛЬШОЙ МОЩНОСТИ

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JOHN B. YOUNG, FARHANG BAKHTAR

Great Britain*

A Comparison Between Theoretical Calculations and Experimental Measurements of Droplet Sizes in Nucleating Steam Flows

Notation

f – friction factor,
g – number of molecules in a droplet of radius r,
P – pressure,
P_0 – nozzle inlet pressure,
$\dot{P}_w$ – rate of expansion at the Wilson point,
q – condensation coefficient,
T_0 – nozzle inlet temperature,
W – nozzle width,
x – axial distance,
σ_∞ – flat film value of surface tension,
σ_r – surface tension of a droplet of radius r.

Introduction

Experimental studies of nucleation in flowing steam have mainly consisted of obtaining the axial pressure distribution in converging-diverging nozzles. Although extremely valuable, these results are insufficient to resolve all the uncertainties in nucleation theory and the measurements of droplet size becoming available provide welcome additional evidence. This paper offers some comparisons between these measurements and theoretical predictions of the same flows.

The theoretical treatment, already described in [1], uses the standard one-dimensional equations of gas dynamics together with classical nucleation theory including the refinements of Kantrowitz [2] and Courtney [3]. Recently Plummer and Hale [4] have published results on the properties of prenucleation water clusters, which suggest that the surface free energy of a small cluster is substantially that obtained from liquid drop theory using the flat film value of surface tension. Consequently the calculations have been carried out with and without the Benson and Shuttleworth surface tension correction

$$\sigma_r=\sigma_\infty\left(1-\frac{1}{3g^{\frac{1}{3}}}\right)$$

as well as using values of unity and 0.036 for the condensation coefficient of water.

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* Department of Mechanical Engineering, University of Birmingham.

The experimental results studied are those by Gyarmathy and Lesch [5], Petr [6], Moore, Walters, Crane and Davidson [7], Krol [8] and Deych, Kurshakov, Saltanov and Yatcheni [9].

1. Method of application

In recent years a tendency has developed to experiment with nozzles having a constant expansion rate in order to facilitate comparisons between different investigations and to provide a quick means of estimating limiting supersaturation ratios and droplet sizes. Furthermore, to avoid two-dimensional problems, investigators tend to give superheated axial pressure traverses of the nozzles instead of their actual shapes. The present authors would like to emphasize that they have no criticism whatsoever of the various methods selected by different investigators to present their results. They do suggest, however, that in addition it would be valuable to have the actual shape of the duct and the inlet conditions of the experiments, as without this information it is impossible to know with any certainty the extent of frictional reheat in the nozzle.

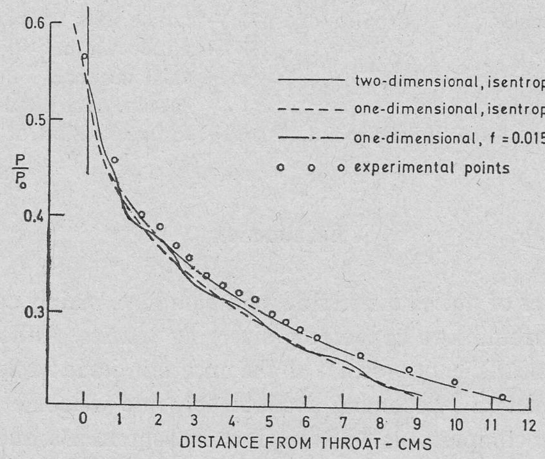

Fig. 1. Two-dimensional and frictional effects in Binnie and Green's nozzle

It has already been shown [10] that the presence of friction affects the results quite markedly and the position may be further clarified by reference to Fig. 1 on which are drawn the superheated curve for Binnie and Green's nozzle [11]. The two-dimensional effects move the location of the sonic point on the axis into the diverging section and for the first centimetre there is good agreement between the two-dimensional isentropic line and the experimental curve. The representation of the flow by an equivalent isentropic area in this region would be completely justified. Beyond this point the one and two-dimensional isentropic results become closer and the difference between these and the experiment is due to friction, which is best included when making a detailed analysis.

In the present analysis, when the actual areas are unavailable, effective areas have been calculated using the superheated curve and allowing for a small friction factor of 0.015 beyond a short distance downstream of the throat.

2. Comparison between theoretical and experimental results

Experiments of Gyarmathy and Lesch [5]

The results analysed are those plotted as Figs. 12.3 and 12.4 of [5]. The equivalent nozzle shape was calculated from the superheated traverse given in [12], but beyond a distance of 2.5 cms downstream of the throat a friction factor of 0.015 has been used. The resulting shape is given in Appendix 1 and a comparison between the present calculations and the results in Fig. 12.3 of [5] is shown in Fig. 2. The axial pressure traverse for the condensing test has not been given in the original, but the location of the zone of rapid condensation has been marked on this diagram. It will be seen from the two curves without correction for surface tension that, although the influence of the condensation coefficient on the limiting supersaturation ratio is small, it has a much greater influence on the droplet size. Because of the correction due to Kantrowitz the effect is very marked at small values of the condensation coefficient, the change in droplet size resulting from an increase of

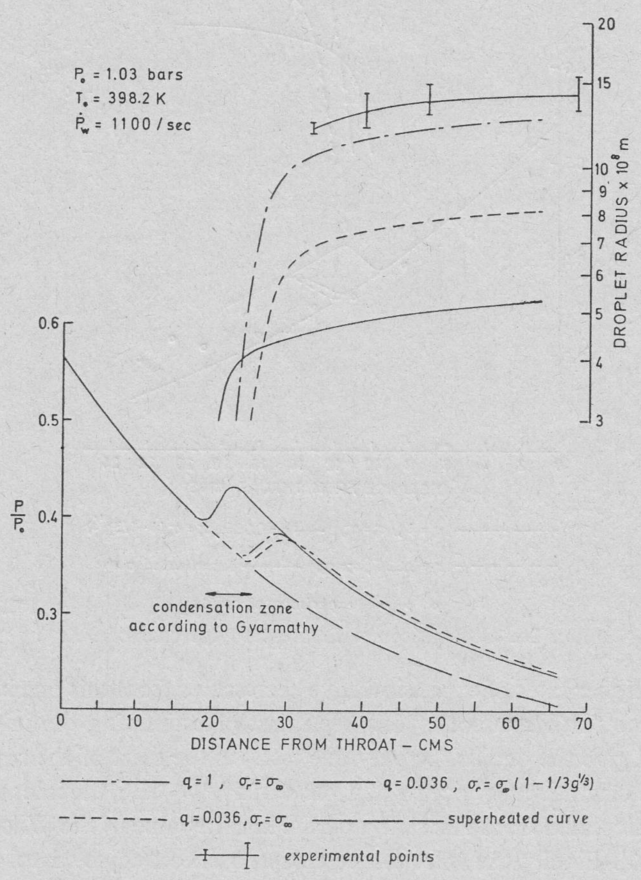

Fig. 2. Comparison with experiments of Gyarmathy and Lesch

q from 0.1 to 1.0 being marginal. In terms of agreement with the measured droplet sizes, best correlation is achieved by using a large condensation coefficient and taking the surface tension of small droplets to be the same as that for a flat surface.

Measurements of Petr [6]

The above measurements are quite extensive and have been performed on nozzles designed for a constant rate of expansion, but a superheated traverse for only the slowest nozzle has been given. Using this curve, scaling off the drawing given in Fig. 10.3 of the original paper for the throat dimensions and adopting a friction factor of 0.015 beyond the first 1.3 cms downstream of the throat has resulted in a duct shape given in Appendix 1.

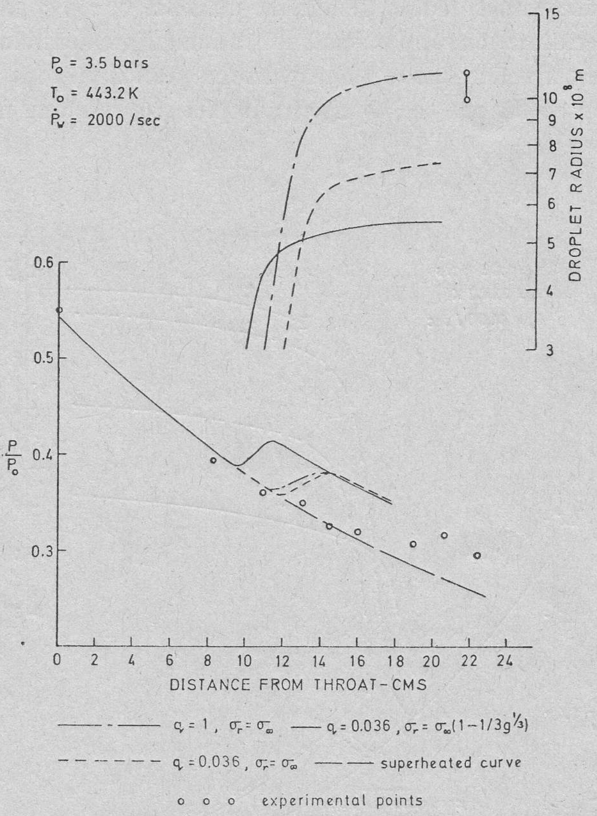

Fig. 3a. Comparison with pressure traverse of Petr

The nozzles with higher rates of expansion have been scaled from this one keeping the throat area the same. One further difficulty has been that of estimating the inlet conditions, as the data provided give the details for only one test. As the start of the rapid condensation in Fig. 10.4 of the original paper occurs at a value of $P/P_0 = 0.36$, the inlet pressures of other tests have been calculated from this ratio and the known value of the Wilson point pressure in Fig. 10.5 of [6]. Finally the inlet temperature has been adjusted to ensure that rapid condensation started at this value of pressure.

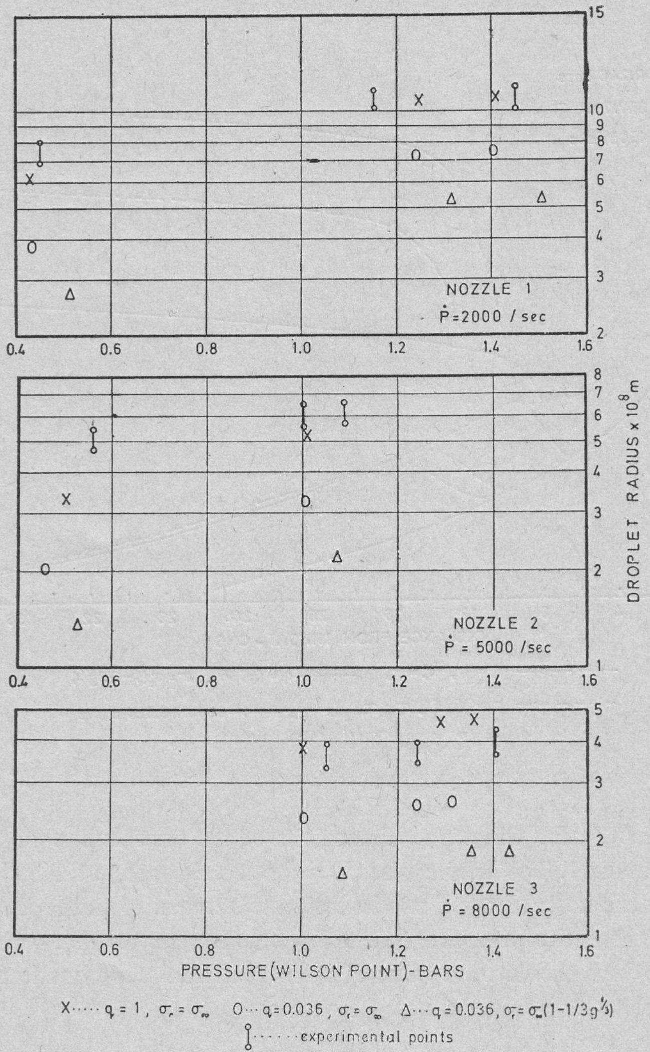

Fig. 3b. Comparison with droplet measurements of Petr

The only possible comparison between theoretical and experimental pressure distribution curves is for the test plotted as Fig. 10.4 in [6] and given in Fig. 3a. To avoid confusion the comparisons with the droplet sizes are given in Fig. 3b for each nozzle separately. The agreement between the theory and these experiments is similar to that observed with Gyarmathy and Lesch. It must be emphasized, however, that the conditions used in the theoretical calculations have been somewhat assumed.

Results of Moore, Walters, Crane und Davidson [7]

These experiments have the advantage that the nozzle dimensions are large in comparison with the boundary layer thickness. It is, therefore, safe to assume the central parts of the flow to be frictionless. The present calculations have been carried out for curve

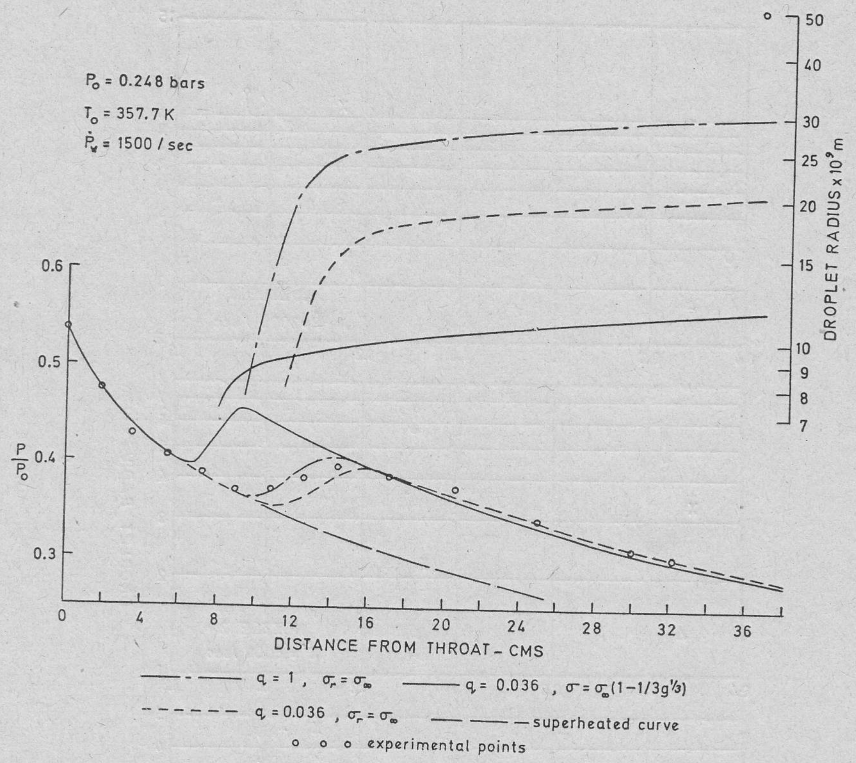

Fig. 4. Comparison with measurements of Moore, Walters, Crane and Davidson

(*b*) in Fig. 37.7 of [7], for which the dimensions of the duct as supplied by Crane [13] are given in Appendix 1. The droplet sizes have been measured at a location 37 cms. from the throat, while the zone of rapid condensation is 12 cms. from the throat. A comparison between the theoretical and experimental results is given in Fig. 4 from which it will be seen that even with the flat film value of surface tension and a condensation coefficient of unity the droplet size is understimated by a factor of 1.7.

Measurements by Król [8]

These are extensive experiments conducted on three nozzles. Complete information about the experiments has been given and the calculations have been carried out for the exact test conditions on nozzles 1 and 2, employing a friction factor of 0.015. A comparison between the theoretical and experimental results for nozzles 1 and 2 is given in Figs. 5 and 6 respectively.

It will be seen that test B in both nozzles gives satisfactory agreement when the flat film value of surface tension and a large condensation coefficient is used. This is consistent with the results previously cited. Test A, however, underestimates the experimental results by a factor of 2 in both cases. It is interesting to consider the rates of expansion at the Wilson points as calculated from the superheated traverse and marked in the diagrams. (The Wilson point pressures are almost identical for the four tests.) In nozzle 1, whereas

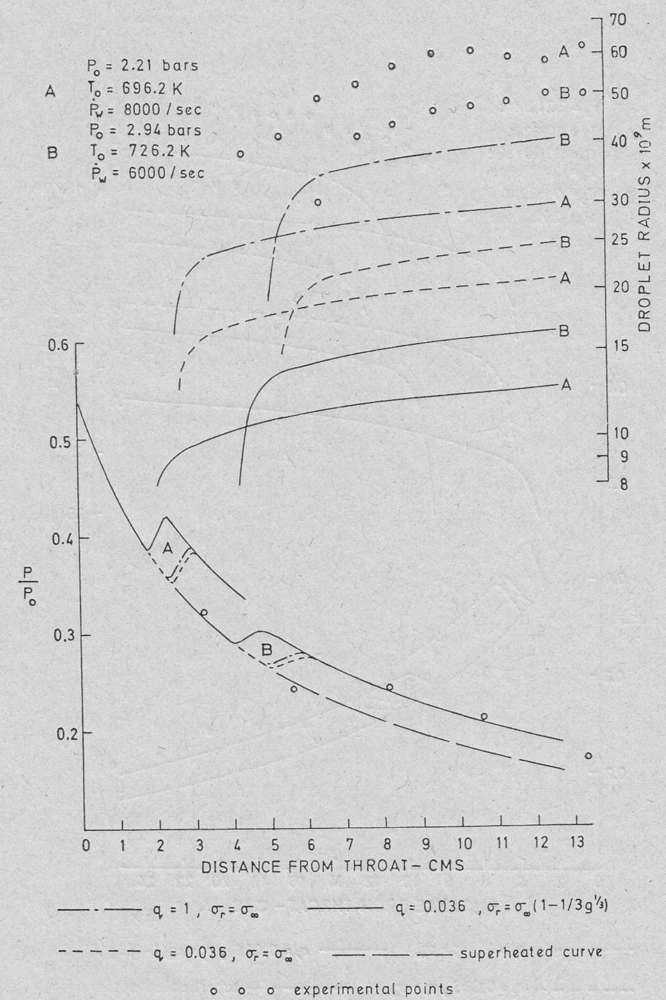

Fig. 5. Comparison with Król's results in nozzle 1

the experiments show an increase in droplet size with rate of expansion, the theory predicts the opposite. The same trend is in evidence in nozzle 2. Further reference will be made to this point in the discussion.

Experiments by Deych and co-workers [9]

The particular results analysed are from an American reproduction of the original. Although the shape of the duct has been given in this publication, the actual drawing is small scale and may have been reproduced from a printed diagram more than once. The above authors, however, state that the duct has been designed for an exit Mach no. of 2 using the method of characteristics and this procedure has been used to obtain the shape used in the calculations. This is given in Appendix 1. A comparison between the theore-

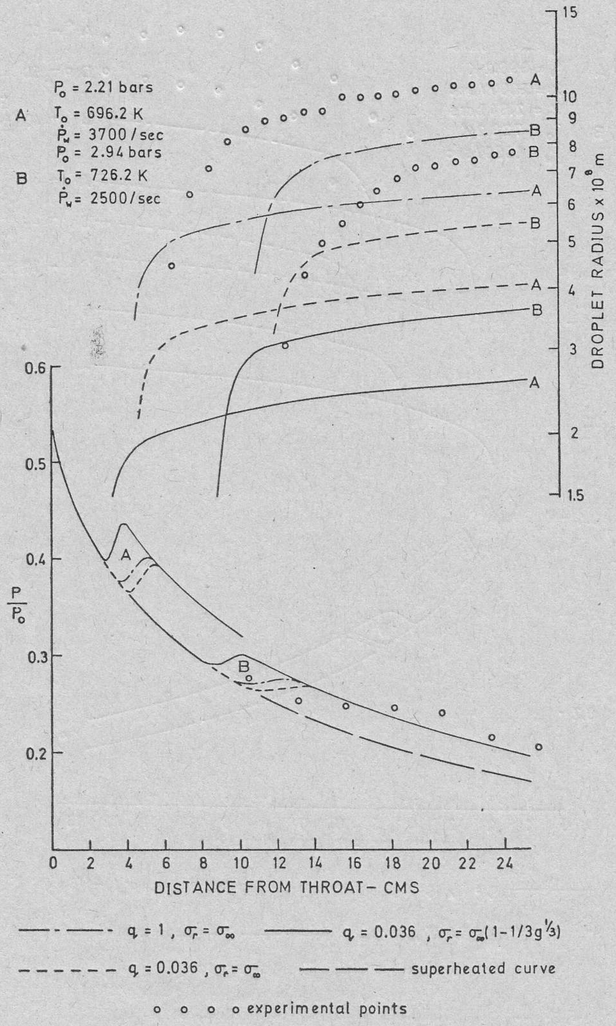

Fig. 6. Comparison with Król's results in nozzle 2

tical and experimental results is given in Fig. 7. A friction factor of 0.015 has been employed after the first 12.5 mm downstream of the throat. The rate of expansion in this expansion has been 19000 per second and it will be seen that even the results using the flat film value of the surface tension underestimate the measurements by an order of magnitude. This tendency is the same as that shown in Tests A of Król's nozzle 1, the larger rate of expansion in the present test giving the greater discrepancy.

3. Discussion

Excepting the tests by Deych and Król at high rates of expansion and irrespective of the arguments at individual steps of the nucleation theory, the measurements of droplet size reported in the literature are mutually consistent.

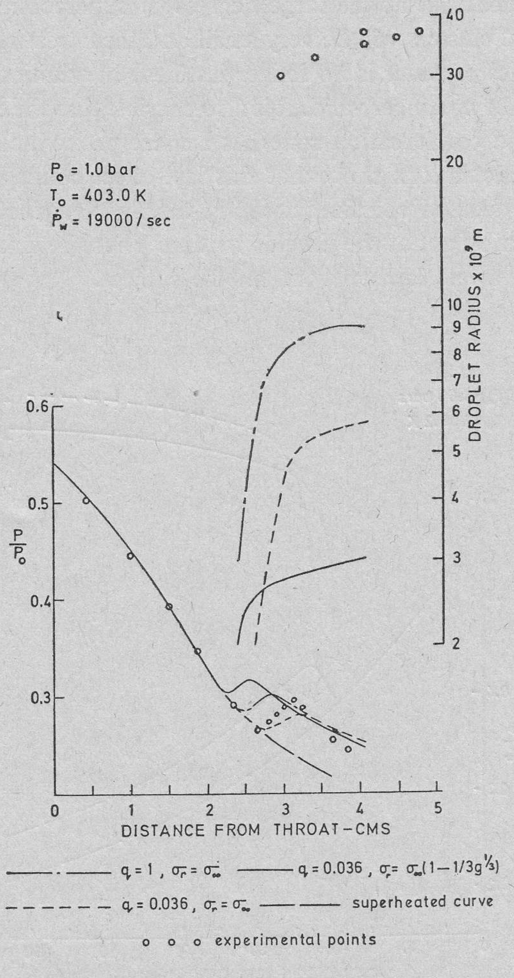

Fig. 7. Comparison with observations of Deych *et al.*

In drawing comparisons between theory and experiment at the moderate and lower rates of expansion, best all round agreement is obtained by using the surface tension of bulk water and a large condensation coefficient but this can only be a tentative conclusion. The droplet populations used in the above calculations are based on using average values. It is known that with the fall in the supersaturation in the rapid condensation zone, the smaller droplets evaporate. Taking the experiment of Gyarmathy and Lesch as an example, a comparison between theoretical solutions with and without allowance for this effect is shown in Fig. 8. It will be seen that, at this rate of expansion, although the refinement of treating the droplets individually does not affect the resulting droplet sizes very greatly, nevertheless it causes further disagreements between the pressure distribution curves. Even so, the overall agreement is still adequate.

The greatest disagreements between calculated and observed droplet sizes occur with experiments of Deych *et al.* and test A nozzle 1 of Krol where the rates of expansion are large. It may be argued that at the large degrees of supercooling associated with these conditions, the critical clusters will be very small and their treatment as spherical droplets with average properties of water is no longer justified. In addition the neglect of the time lag in nucleation may be no longer valid. It is also possible that the evaporation of the smaller clusters in the rapid condensation zone has a more pronounced effect in these experiments. Preliminary calculations show that this last effect could account for most of the discrepancy but full detailed solutions treating the droplets individually for these tests have not yet been carried out at the time of writing. Thus the final verdict on this aspect of the problem must await further work on the subject.

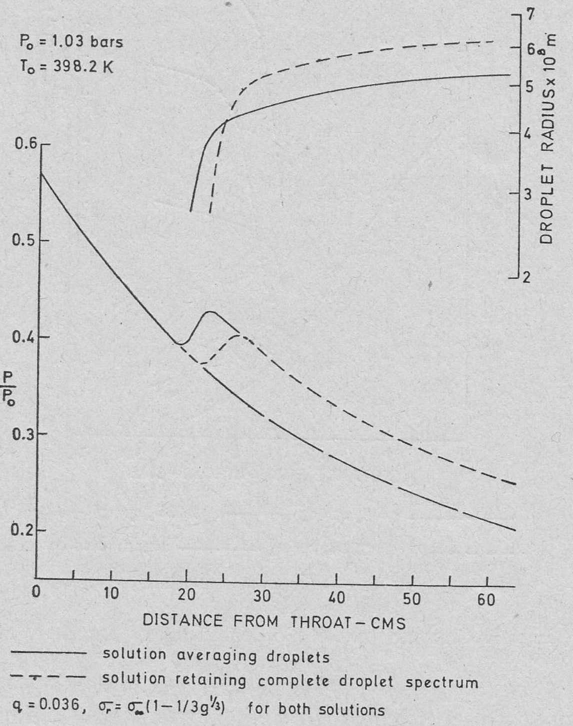

Fig. 8. Effect of averaging droplets

Therefore, although it is hoped that with further progress, the agreement between theory and experiment can be improved, in the mean time, particularly as in the majority of practical cases of nucleation in flowing steam, the rates of expansion are low and within the range of the majority of results, the error caused by averaging the droplets seems to balance the effect of the unknowns.

Acknowledgements. The investigations reported in this paper have been supported by a grant from the Science Research Council. The authors are also grateful to Mr. M. Piran for help with some of the results presented.

Appendix 1

The width of each nozzle, W [mm], has been expressed in terms of a polynomial in the axial distance, x [mm]. Usually this required two equations in which case the value of x in the first is measured from the throat and that in the second from the change over point.

Gyarmathy and Lesch

$f=0$ for the first 25 mm and 0.015 subsequently.

$0<x<254$, $W=31.79+1.463\cdot 10^{-4}x^2-2.527\cdot 10^{-7}x^3$

$254<x<635$. $W=37.09+0.03366x$

Nozzle depth $=44.0$ mm.

Petr

$f=0$ for the first 12.5 mm and 0.015 subsequently.
1) $\dot{P}=2000/\mathrm{s}$

$0<x<75.6$, $W=29.0+4.256\cdot 10^{-4}x^2-1.659\cdot 10^{-6}x^3$

$75.6<x<180$, $W=30.72+0.03618x+1.941\cdot 10^{-3}x^2-1.519\cdot 10^{-6}x^3$

Nozzle depth $=30.0$ mm.
2) $\dot{P}=5000/\mathrm{s}$

$0<x<30.48$, $W=29.0+1.047\cdot 10^{-3}x^2$

$30.48<x$, $W=29.97+0.06382x+7.280\cdot 10^{-4}x^2-1.938\cdot 10^{-6}x^3$

Nozzle depth $=30.0$ mm.
3) $\dot{P}=8000/\mathrm{s}$

$0<x<19.05$, $W=29.0+2.886\cdot 10^{-3}x^2$

$19.05<x$, $W=30.05+0.11x+9.842\cdot 10^{-4}x^2$

Nozzle depth $=30.0$ mm.

Moore, Walters, Crane and Davidson

$f=0$

$0<x<10.16$, $W=100.29-1.370\cdot 10^{-4}x^2+2.944\cdot 10^{-4}x^3$

$10.16<x<381$, $W=100.58+0.08839x$

Nozzle depth $=152$ mm.

Król

1) Nozzle 1
$f=0$ for first 15 mm and 0.015 subsequently

$0<x<1.27$, $W=29.60+6.299\cdot 10^{-3}x^2$

$1.27<x<305$, $W=30.62+0.16x$

Nozzle depth $=25$ mm.

2) Nozzle 2

$f=0$ for first 10 mm and 0.015 subsequently

$0<x<15.24, \quad W=29.60+2.578\cdot 10^{-3}x^2$

$15.24<x<254, \quad W=30.20+0.07857x$

Nozzle depth = 25 mm.

Deych

$f=0$ for first 12.5 mm and 0.015 subsequently

$0<x<18.12, \quad W=32.98+0.03338x-4.108\cdot 10^{-3}x^2+6.321\cdot 10^{-4}x^3$

$18.12<x<40.6, \quad W=36.00+0.50712x-1.212\cdot 10^{-3}x^2-1.047\cdot 10^{-4}x^3$

Assumed nozzle depth = 25 mm.

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Porównanie obliczeń teoretycznych z wynikami badań doświadczalnych wielkości kropel w przepływie pary wodnej z zarodkami kondensacji

Streszczenie

W artykule porównuje się pomierzone wielkości kropel powstałych na drodze tworzenia się zarodków kondensacji w przepływie pary wodnej z teoretycznymi przewidywaniami dla takich samych przepływów.

Skorzystano z wyników doświadczalnych, które podali Gyarmathy, Petr, Król, Moore, Walters i in. oraz Deych i in. W analizie teoretycznej posłużono się jednowymiarowymi równaniami przepływu oraz klasyczną teorią powstawania zarodków kondensacji z poprawkami wyprowadzonymi przez Kantrowitza i Courtneya. Najlepszą zgodność teorii z doświadczeniem uzyskano posługując się naprężeniem powierzchniowym wody w dużej objętości oraz przyjmując duży współczynnik kondensacji.

Сравнение результатов теоретических расчетов с результатами экспериментальных исследований размеров капель в потоке влажного пара, в котором образуются зародыши конденсации

Резюме

В статье сравниваются результаты исследования размеров капель, возникших ввиду образования зародышей конденсации в потоке водяного пара, с теоретическими предвидениями для таких же самых течений.

Использованы экспериментальные результаты, полученные Гьярмати, Петром, Кролем, Муром, Уолтерсом и др., а также Дейчем и др. Теоретический анализ основан на одномерных уравнениях течения и на классической теории возникновения зародышей конденсации, с поправками, введенными Кантровичем и Куртнеем. В большинстве случаев наилучшей сходимости результатов исследований достигли пользуясь поверхностным натяжением воды в большом объеме и принимая большие значения коэффициента конденсации.