A robust 'time-marching' solver for one-dimensional nucleating steam flows

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A mixed Lagrangian/Eulerian 'time-marching' solver capable of predicting one-dimensional nucleating steam flows is described. Simple nucleation and droplet growth models are employed which avoid the use of variable empirical factors and which have been validated using existing experimental data from nozzle experiments performed in the steam tunnel of the Central Electricity Research Laboratories. Theoretical predictions are compared against experimental results encompassing all flow regimes likely to be encountered in a one-dimensional analysis of flow in a low pressure steam turbine. These include supercritical heat addition cases which display both steady and unsteady shock wave formation.

Keywords: *steam turbines, nucleating steam flows, aerodynamic shock waves, time-marching solver*

Introduction

Techniques have recently been developed which enable the wetness fractions and mean droplet diameters to be measured at various positions within large, low pressure steam turbines used for electrical power generation[1]. In order to gain a better understanding of the condensation loss processes involved, it was decided to attempt a theoretical prediction of these measurements, initially by solving the set of one-dimensional flow equations as an initial value problem. A computer program was written for this purpose using a fourth-order Runge–Kutta integration method, and a procedure mentioned in Ref 2 was employed to extrapolate across the sonic singularity. Equivalent one-dimensional geometries were then generated which would represent the principal features of the three-dimensional flow through a machine. However, it was discovered that droplet nucleation was regularly predicted to occur before or near the position where the flow becomes sonic, and such cases are extremely difficult, if not impossible, to solve using the Runge–Kutta program.

It has been shown variously (eg Refs 3, 4 and 5) that 'time-marching' methods produce useful solvers for the analysis of both one- and two-dimensional condensing steam flows. This paper describes the predictions of a 'time-marching' algorithm which was subsequently written and which is able to solve for all flow regimes likely to be encountered in low pressure steam turbines.

Nucleation and droplet growth theory

There are numerous theories in the literature describing the processes of homogeneous nucleation and the subsequent growth of droplets in a supersaturated vapour. The choice of the theory to be used in the current analysis was based on the criteria that it should be simple, should not include any variable empirical factors, and should be suitably validated using experimental results from the relevant range of steam conditions.

There has long been established a classical nucleation theory (eg Ref 6) which estimates the free energy of the microclusters produced by random kinetic collisions of vapour molecules in terms of the surface free energy and the chemical potential of the bulk condensed phase—the so-called 'capillary approximation'. Despite criticisms that the surface free energy of molecular agglomerates cannot be equal to that of the bulk phase and that cluster translation and rotation have been neglected, classical theory has often proved as successful in predicting nucleation rates as have more refined models (eg Ref 7). It predicts that the probable rate of production of microclusters having a radius equal to a critical radius which is stable at the particular thermodynamic conditions, is given by

$$J_{\text{iso}}=\left(\frac{2\sigma n_{\text{m}}^3}{\pi}\right)^{1/2}\left(\frac{\rho_{\text{g}}}{\rho_{\text{f}}}\right)\exp\left\{\frac{4\pi r_{\text{crit}}^2\sigma}{3kT_{\text{g}}}\right\}$$

where

$$r_{\text{crit}}=\frac{2\sigma}{\rho_{\text{f}}RT_{\text{g}}\Lambda}$$

and

$$\Lambda=\ln\left(\frac{p}{p_{\text{s}}(T_{\text{g}})}\right)$$

It was first noted by Kantrowitz[8] that this isothermal approach neglects the fact that inelastic collisions will cause the energy of a cluster to change, and therefore it cannot be considered to have the same temperature as the surrounding vapour. The nonisothermal model was later refined by Feder *et al*[9], but despite their differing treatments of the problem the corrections they propose are very similar, that of Kantrowitz being given by

$$J_{\text{niso}}=\frac{J_{\text{iso}}}{(1+\phi)}$$

where

$$\phi=2\frac{(\gamma-1)}{(\gamma+1)}\frac{h_{\text{fg}}}{RT_{\text{g}}}\left(\frac{h_{\text{fg}}}{RT_{\text{g}}}-\frac{1}{2}\right)$$

Once stable droplets have been nucleated they proceed to grow in the supersaturated vapour. A growth law based on the macroscopic concepts of heat and mass transfer were derived by Gyarmathy[10]; a modified version, used by Jackson and Davidson[2], is given by

$$\dot{m}_j=\dot{q}_j/(h_{\text{g}}-h_j)$$

where

$$q_j=4\pi r_j^2\alpha_j(T_j-T_{\text{g}})$$

and

$$\alpha_j=\frac{\kappa_{\text{g}}}{2r_j}\frac{Nu_{\text{o}}}{[1+Sc\{(8\pi)^{1/2}/1.5\}(Kn_j/Pr)(\frac{1}{2}Nu_{\text{o}})]}$$

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The group Sc is equal to unity unless a correction suggested by Schrage[11] is included. This correction arises from the fact that when there is a net condensation occurring onto a droplet, a vapour bulk mass flow is induced, directed normally towards the droplet surface. The inclusion of this modification in the kinetic theory calculations results in an expression for the Schrage correction:

$$Sc=(2-q_c)/2q_c$$

We define the condensation coefficient q_c to be the fraction of molecules incident upon a droplet which can be considered as having condensed. Since there is no firm experimental or theoretical evidence as to the value this coefficient should take, it is assumed to be unity.

Moore *et al*[12] present results for five condensing steam nozzle experiments: four (A, B, C, D) with dry inlet and initial superheat, and a further test (E) with wet inlet. It was found using the Runge–Kutta program that good agreement with experiment could be obtained both for droplet size and pressure distribution using nonisothermal classical nucleation theory and Schrage corrected growth laws, provided the truncated virial equation of state proposed by Bakhtar *et al*[13] is used to describe the vapour phase, ie

$$p=\rho_g RT_g(1+B\rho_g)$$

where

$$B=\{2.0624-(2612.04/T_g)10^{[100800/(T_g2+34900)]}\}10^{-3}\,\mathrm{m^3\,kg^{-1}}$$

Governing equations and solution procedure

The time-marching method selected was MacCormack's explicit and second-order method[14], a simple and popular algorithm of the Lax–Wendroff type which possesses several potentially advantageous properties. It is capable of capturing shock waves which will be present if the nozzle is rechoked thermally, and, because of the 'real time' nature of the calculation, it should be able to detect whether these shocks are stable or unsteady. Also, this method may be extended to two dimensions should such a solver ultimately be required.

Preliminary investigations indicated that a simply coded (ie equal grid spacing) complete Eulerian solver was unlikely to efficiently provide adequate resolution over the nucleation zone for an accurate solution. This is because the thermal relaxation times associated with the very small droplets are much smaller than the timestep required for gas field stability. It was therefore decided to employ a mixed solution technique in which the gas and liquid phase calculations are completely decoupled and therefore do not use the same computational grid. The gas phase is treated using the Eulerian solver which generates a particular gas field, thus providing the information required for droplet nucleation. A Lagrangian style integration is used to track the growth of a droplet from each stable group through this gas field using a second-order Runge–Kutta technique; the wetness fraction being determined from the conservation of droplet number. The exchanges of mass, momentum and energy between the phases are then incorporated into a subsequent gas field Eulerian step in the form of source terms. This method is easy to program and avoids unnecessary refinement of the gas field grid. However, the decoupling of the phases must result in a diminished ability to predict unsteady flows, since the gas field is effectively fixed momentarily in a pseudo-steady state whilst the droplet growth integrations are performed.

The equations governing the gas field behaviour are expressed in conservation form. In one dimension:

$$\frac{\partial U}{\partial t}+\frac{1}{A}\frac{\partial F}{\partial x}=S$$

where U is the vector of dependent variables, F is the vector describing mass, momentum and energy fluxes, and the source term vector S represents the interphase transfer processes (and a geometrical correction to the momentum equation).

The calculation then proceeds by a 'two-step' numerical integration which alternately uses forward and backward differences for the two steps:

$$\tilde{U}_i^{n+1}=U_i^n-(F_{i+1}-F_i)\,\delta t/(A\,\delta x)+S_i\,\delta t$$

$$U_i^{n+1}=\tfrac{1}{2}(U_i^n+\tilde{U}_i^{n+1})-\tfrac{1}{2}(\tilde{F}_i-\tilde{F}_{i-1})\,\delta t/(A\,\delta x)+\tfrac{1}{2}\tilde{S}_i\,\delta t$$

Notation

A	Cross-sectional area of nozzle
a	Frozen speed of sound
c	Gas velocity
D	Drag coefficient
d	Droplet diameter
e	Specific internal energy
F	Flux vector
h	Specific enthalpy
J	Nucleation rate
Kn	Droplet knudsen number
k	Boltzmann's constant
m	Droplet mass
$\dot{m}$	Rate of droplet growth
Nu_o	Droplet nusselt number (=2)
n	Number per unit mass
n_m	Number of molecules per unit mass
Pr	Prandtl number (=0.9)
p	Pressure
$\dot{q}$	Rate of heat transfer
R	Gas constant
S	Source term vector
s	Specific entropy
T	Temperature
t	Time
U	Dependent variable vector
u	Droplet velocity
w	Nozzle throat dimension
x	Distance down nozzle
y	Wetness fraction
γ	Isentropic exponent
κ	Thermal conductivity
μ	Viscosity
ρ	Density
σ	Surface tension

Subscripts

corr	Correction
crit	Critical
f	Liquid
fg	Difference between gas and liquid states
G	Geometrical
g	Gas
I	Describing interphase transfer
i	Grid point
isen	Isentropic
iso	Isothermal
j	Droplet group
niso	Nonisothermal
o	Total
s	Saturation
32	Sauter mean

Superscripts

n	Calculation step

where

$$U=\begin{pmatrix}\rho_g\\ \rho_g^c\\ \rho_g(e_g+\frac{1}{2}c^2)\end{pmatrix}$$

$$F=\begin{pmatrix}\rho_g cA\\ \{(p-p_{corr})+\rho_g c^2\}A\\ \rho_g cA(h_g-p_{corr}/\rho_g+\frac{1}{2}c^2)\end{pmatrix}$$

$$S_G=\begin{pmatrix}0\\ (p/A)\,dA/dx\\ 0\end{pmatrix}$$

$$S_I=\begin{pmatrix}-\rho_g/(1-y)\sum_j(n_j\dot{q}_j/h_{fg}+J_jm_j)\\ -\rho_g/(1-y)\sum_j\{n_jD_j+c(n_j\dot{q}_j/h_{fg}+J_jm_j)\}\\ \rho_g/(1-y)\sum_j\{n_j\dot{q}_j-n_jD_ju_j-(h_s+\frac{1}{2}c^2)(n_j\dot{q}_j/h_{fg}+J_jm_j)\}\end{pmatrix}$$

and

$$S=S_G+S_I$$

For a completely general solution, droplet velocities u_j would be determined by solving the droplet momentum equations, although for very small droplets it is convenient to approximate the droplet motion. This may be done by neglecting slip between phases and setting $u_j=c$ or, more exactly, by neglecting the acceleration of relative phase velocities and taking $u_j=c-\tau_j c(\partial c/\partial x)$ where τ_j is the kinematic relaxation time. It can be shown (eg Ref 2) that introducing zero slip assumptions in the interphase transfer terms retains the correct sonic propagation properties of the two-phase medium.

The criterion for stability of the explicit gas field solution is given by the Courant–Friederichs–Lewy (CFL) condition which restricts the computational timestep $\delta\tau t$ according to the relation

$$(|c+a|)\,\delta t/\delta x\leqslant 1$$

This method should be able to predict aerodynamic shocks with only slight smearing; however, 'ripples' in the gas field are characteristically produced by algorithms of the Lax–Wendroff type around these shocks. In order to cope with such problems the concept of an explicit artificial viscosity was introduced by von Neumann and Richtmyer[15] in the form of a pressure correction term:

$$p_{corr}=\alpha\frac{\partial c}{\partial x}$$

where, as given by Tyler[16]:

$$\alpha=b\,\delta x\,\rho_g(|c|+a)$$

and the amount of this numerical damping to be included is determined by the factor b.

The flow field which is calculated by this algorithm is defined by the boundary conditions imposed upon it. All cases investigated have a subsonic inflow and a supersonic outflow: at the outflow boundary no intervention is required provided backward differences are used for both predictor and corrector steps, steady conditions being maintained at the inflow boundary.

For convenience a new droplet group is considered to be nucleated over each gas field grid spacing in the nucleation zone, and this resulted in up to twenty-five stable droplet groups being carried in the calculation. Since the computational time required to execute the Lagrangian sum for all the droplet groups is much greater than that required for the Eulerian step it was decided to investigate the effect of varying the relative frequency of the Eulerian and the Lagrangian calculations. Comfort *et al*[17], who use a similar technique to investigate the behaviour of both low and high quality two-phase steam–water flow, state that in their regime it was found that a ratio of one for one proved optimum both for stability and calculation speed. However, they do not consider interphase transfer processes, and it was discovered that in the regime of smaller, more active, droplets with which we are concerned, one Lagrangian calculation for every ten Eulerian steps was adequate with respect to the above criterion and did not alter the solution for unsteady flows. It should be noted that the droplet source terms are re-evaluated after each Eulerian step, since the temperature gradient which drives the interphase transfer is altered as the gas field changes.

Subcritical heat addition

As steam expands through a transonic nozzle, a metastable state of supersaturation develops. Equilibrium is restored by condensation onto the tiny stable droplets formed by the process of homogeneous nucleation. The release of heat into the flow associated with condensation will cause the flow to tend towards a Mach number of unity. If the flow is initially supersonic then there exists a critical amount of heat, Q_{crit}, just sufficient to return the flow to the sonic condition. In the case where the heat released $Q<Q_{crit}$, the flow remains supersonic and often displays an increase in pressure known, somewhat misleadingly, as a condensation shock. The results Moore *et al*[12] present for tests made on nozzles A, B, C and D are all examples of this subcritical heat addition. We shall refer to these as tests A_1, B_1, C_1 and D_1 and the wet inlet run made using nozzle E as test E_1. The agreement obtained with experimental results (and the predictions of the Runge–Kutta program) for these cases using the time-marching program would reveal whether any spurious numerical effects which may be associated with this time-marching algorithm have in some way affected the solution. It soon became clear that the positions of the onset of nucleation and of the subsequent condensation shock were affected by the degree of numerical damping included in the solution. Fig 1 compares the pressure distributions around the condensation shock produced for test B_1 with different values for the factor b. It can be seen that the effect of numerical viscosity is to delay the onset of nucleation and the position of the condensation shock; good agreement with experiment being obtained using $b=0$. The predicted droplet size at the position of measurement is found to increase from $d_{32}=0.94\,\mu m$ to $d_{32}=1.02\,\mu$m as b increases from 0 to 0.4. Thus, with no explicit artificial viscosity used in the solution, the time-marching program reproduces almost exactly the prediction of the Runge–Kutta program. The agreement with experiment for tests A_1, C_1, D_1 and E_1 by taking $b=0$ is shown in Fig 2. An inlet wetness of 0.9% is used in the prediction of test E_1 which was calculated from the measured steam tunnel turbine work extraction. The flow is assumed to be non-nucleating, and good experimental agreement is obtained using an inlet mean droplet diameter of $d_{32}=1\,\mu$m as found in Ref 12.

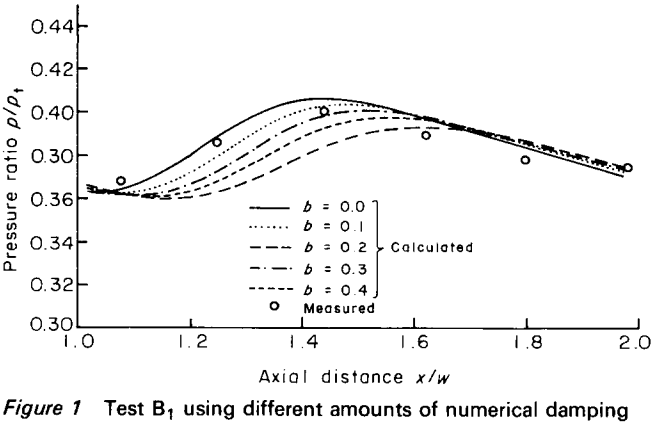
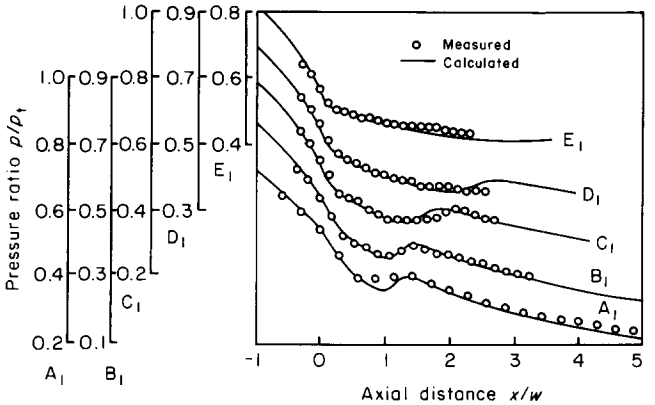


Figure 1 Test B_1 using different amounts of numerical damping



Test	A_1	B_1	C_1	D_1	E_1
Measured d_{32}, μm	0.05	0.10	0.15	0.14	1.50
Calculated d_{32}, μm	0.06	0.09	0.14	0.17	1.48

Figure 2 Comparison of theory with experiment for results presented in Ref 12

Table 1

Test	C_2	D_2	E_2
Tot. press., bar	0.2474	0.2425	0.2449
Tot. temp., K	347.3	340.0	346.7

Supercritical heat addition

The phenomenon of supercritical heat addition occurs if the heat released into an initially supersonic flow $Q \geq Q_{crit}$, and this results in an aerodynamic shock forming in the flow. This shock wave will either be stable or unsteady, depending on the extent by which Q exceeds Q_{crit}. As mentioned in Ref 12, supercritical heat addition was observed in further nozzle tests, particularly in those nozzles having lower expansion rates. We shall analyse the results from one such test made on each of the three nozzles with lowest expansion rates, which we shall call tests C_2, D_2 and E_2. The inlet conditions for these tests are given in Table 1.

For a critical or moderate supercritical heat addition the shock wave formed in the nozzle remains stable, and tests C_2 and E_2 both appear to be of this type. The experience gained in analysing the subcritical cases indicates that, ideally, we do not wish to include any artificial viscosity. It was found, however, that for very low values of the factor b, 'ripples' developed upstream of the shock which interfered with the nucleation zone, and subsequent wetness effects became unreliable. Fig 3 compares solutions in which different values of the factor b are used for test E_2. This reveals that we require a value of $b \approx 0.1$ in order that a smooth pressure variation is produced around the shock, the predicted position of this shock being only slightly delayed. The agreement with experimental data is shown in Fig 4, and we see that the droplet size prediction is extremely good. It is worth noting that this size is much greater than those found in the subcritical cases and is consequently a more accurate measurement. This is because the extinction droplet sizing technique used has improved resolution for these larger droplets, with a greater number of those optical wavelengths investigated exhibiting distinct transmission coefficients. Fig 5 shows the comparison with the results of test C_2, again taking $b = 0.1$; here the agreement with measured droplet size appears less good, although it should be remembered that we are dealing with small droplets where experimental uncertainty is greater (it is also possible that 'ripples' near the nozzle throat may have slightly affected the prediction of nucleation phenomena).

In both cases the theoretically predicted increase in pressure at the shock is greater than that indicated experimentally, and the pressure then proceeds to decrease at a faster rate than do the measurements. This effect is much more pronounced in test E_2, which has a slower expansion rate. Since these discrepancies are absent in the subcritical cases then they are most probably due to the presence of a shock wave in the flow. We know that a shock wave will thicken the boundary layer downstream, and this change in the effective duct geometry could explain the error in the pressure distribution 'tail'. Also, all measurements are made using wall tappings, and around the shock wave it is likely that they do not accurately represent the 'in-stream' static pressure, since the shock is 'smeared' at the wall because of boundary layer interaction.

A factor worth consideration is that in the above solutions the droplet velocity was set equal to the gas velocity—an assumption which is usually considered to be reasonable for

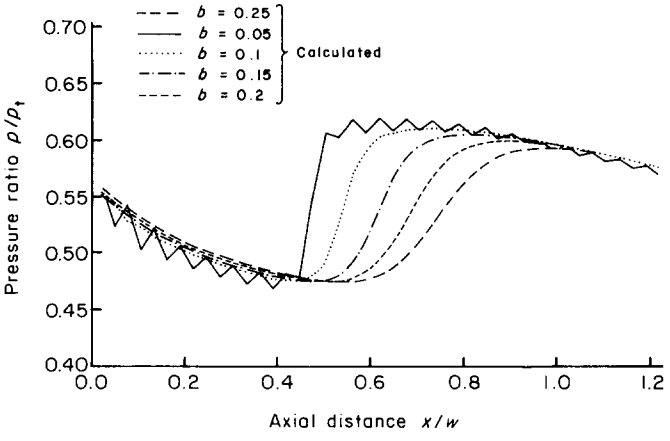


Figure 3 Test E_2 using different amounts of numerical damping

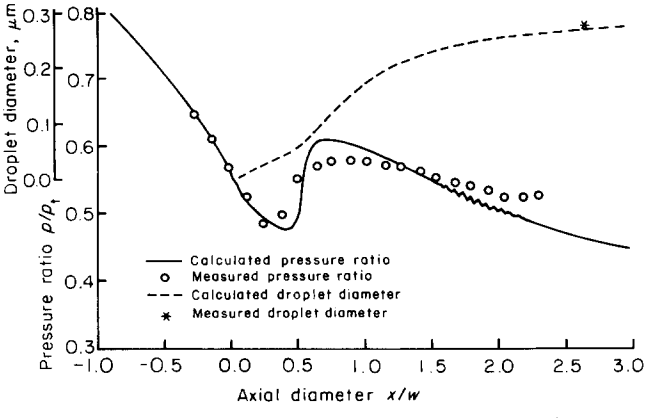


Figure 4 Comparison of theory (b=0.1) with experiment for test E_2

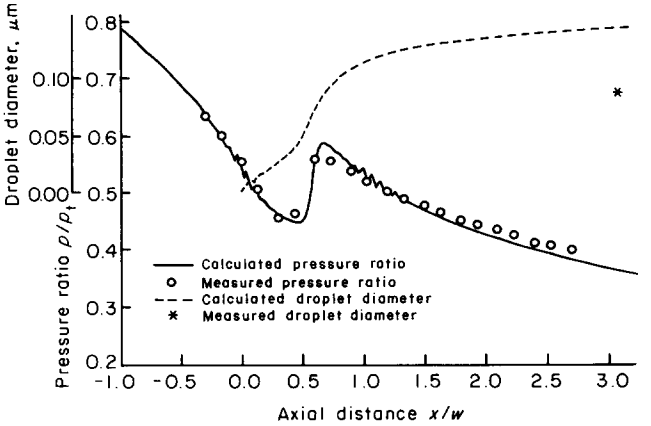


Figure 5 Comparison of theory (b=0.1) with experiment for test C_2

small (submicron) droplets. However, any effect of this simplification will be magnified by the abrupt changes in velocity associated with shock waves. In order to assess the importance of including slip between phases in the calculation the approximate expression for droplet velocity given earlier was adopted, along with the expression for drag coefficient used in Ref 2. Its inclusion resulted only in a slight decrease in droplet size and a slight increase in the pressure downstream of the shock, thus demonstrating that neglecting the drag of the droplets on the gas phase remains a good approximation.

Unsteady flow

In the situation where $Q \gg Q_{crit}$ it is known that the flow does not remain stable (eg Refs 18 and 19). The heat released into the flow as vapour condenses onto the nucleated droplets causes a shock wave to develop which moves upstream towards the nucleation zone. (In a stable case it was found that the catastrophic collapse of subcooling at the shock wave defined the end of nucleation.) The temperature of the flow immediately before the condensation zone is increased by the presence of the shock wave, thus causing the supercooling, and hence the nucleation rate, to decrease. This results in less heat being released in the condensation zone, and consequently the shock begins to weaken. Also, if the nucleation occurs in the transonic region of the nozzle then the shock wave readily reaches the throat, and as it moves into the convergent section of the nozzle it weakens further. The change in flow conditions causes supersaturation to deepen and the nucleation rate to increase, and the ensuing release of heat in the condensation zone thus initiates a new cycle.

At first sight it is unclear how a mixed calculation technique will behave when confronted with an unsteady flow of this type. The times taken for one oscillation cycle, as quoted by Barschdorff[18], are comparable to the time taken for a droplet to travel down the duct, and therefore the steady Lagrangian droplet calculation cannot faithfully represent the true dynamic behaviour. However, the 'perturbation' nature of this solver should certainly enable it to detect when a solution is not stable and provide adequate predictions for the relaxation times associated with information transferred via the gas phase. The only major inaccuracy is likely to be that the downstream gas field 'learns' about the changes in nucleation rate too quickly, probably resulting in a predicted frequency which is too high (Appendix).

For test D_2 the program predicted an oscillating flow, the nature of which is very similar to that described above. Nucleation of stable droplets commences several grid spacings before the throat and causes a shock wave to develop which moves upstream, reduces the nucleation rate and weakens, enabling renewed nucleation to cause another shock wave to develop. The predicted frequency of this fluctuation was $\nu \approx 300$ Hz, and Fig 6 shows the state of the flow at the approximate times of maximum the minimum nucleation. We see that the predicted droplet size varied from a value much smaller than that measured to one much greater, corresponding to changes in the number of nuclei formed. The measurement of $d_{32} = 0.45\ \mu$m is considerably greater than anything previously encountered, and a time average of the predicted droplet sizes is in quite close agreement with this measurement. Obviously, the axial mean droplet size distributions shown in Fig 6 will be very inaccurate, and a more realistic distribution would involve a combination of the two pseudo-steady states they describe. The result of the error in the heat released into the latter stages of the nozzle should not be too great, since the flow is tending towards a state of equilibrium.

Another factor which is important in the analysis of an oscillating flow is the amount of numerical damping to be included. It was found that, as for the steady case, a value for b of 0.1 was required to remove the ripples around the shock wave. By increasing b to 0.2 the unsteadiness was reduced to little

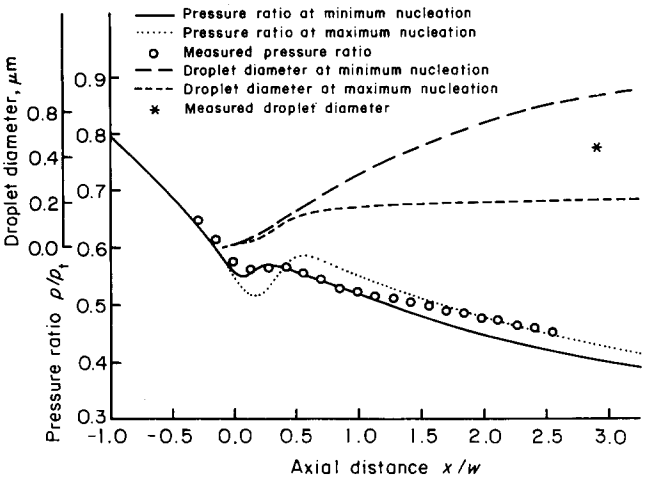


Figure 6 Test D_2 at approximate times of maximum and minimum nucleation

more than small fluctuations about a shock wave, the frequency of this oscillation being greater than that for the case where $b = 0.1$; whilst with $b = 0.3$ the unsteadiness was completely removed and a perfectly stable solution produced. The question therefore arises as to whether the flow was unsteady or in fact steady. Schlieren photographs taken during this test and centered about tapping four show variously a shock or no shock; when the shock is visible it is in different positions and also curved in a different sense. This strongly suggests that test D_2 was indeed an unsteady case.

Conclusion

A mixed Eulerian/Lagrangian solver has been developed which is capable of predicting nucleating steam flows for both sub- and supercritical levels of interphase heat exchange. With no added numerical viscosity the subcritical nozzle results of Ref 12 are predicted accurately, and this algorithm reproduces almost exactly the solution of a Runge–Kutta program using the same growth and nucleation theories which are purely phenomenologically based. The program carries up to twenty-five droplet groups and converges in a reasonable computer time (about one minute using an Amdahl 5870 processor). With the inclusion of a small amount of numerical viscosity to remove the ripples in the solution from around shock waves, this algorithm is able to cope with supercritical flows (convergence for steady cases taking approximately twice as long as for the subcritical cases). Although still very adequate, agreement with experimental pressure distributions is less good in these cases. This is very probably due to the interaction between the wall and the shock wave and subsequent boundary layer thickenings. This calculation method was also able to predict the occurrence of an unsteady flow pattern provided that only a small quantity of numerical damping was included, although it is uncertain whether this flow was modelled very accurately, particularly with respect to the oscillation frequency. The droplet sizes measured in two of the cases are much greater than those found in the subcritical flows, and they were accurately predicted by the program.

The solver has proved robust for all regimes of nucleating steam flow likely to be found in a low pressure steam turbine, and the difficulties encountered in attempting a one-dimensional turbine analysis using a Runge–Kutta program should no longer be a problem.

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Appendix

Wegener and Mosnier[19] describe an approximate method for determining the frequency of an oscillation. Let Δx be the distance between the nucleation zone and the condensation zone. The shock wave generated moves upstream with velocity v_s, causing a temperature increase which 'quenches' nucleation after a time $\tau_1 = \Delta x(v_s - c_k)$ where c_k is the flow velocity at the onset of condensation. After a further time $\tau_2 = \Delta x/(c_k - c_2)$ the nuclei stop arriving and the heat addition ceases, c_2 being the changed flow velocity imposed by the shock. This change in heat addition causes expansion waves to be generated which travel upstream at the local speed of sound, a, causing the temperature in the nucleation zone to drop at a time $\tau_3 = \Delta x/\{a-(c_k - c_2)\}$ later. The newly generated nuclei are then able to release heat again after a further time $\tau_4 = \Delta x/c_k$. Consequently, we have a cycle frequency $\nu \approx 1/(\tau_1 + \tau_2 + \tau_3 + \tau_4)$.

Using this breakdown of the oscillation mechanism it is easy to see where the mixed calculation method becomes inaccurate. There is no clear reason that the program will not be able to predict reasonable values for the time intervals τ_1 and τ_3. However, due to the fact that gas field 'real' time is made to stand still whilst droplets propagate down the duct, then the time intervals τ_2 and τ_4 are effectively reduced to zero. Thus it is likely that the mixed calculation technique would produce an oscillation frequency more accurately approximated by $\nu \approx 1/(\tau_1 + \tau_3)$.

Book review

Computational Methods in Viscous Flow III

Ed. W. G. Habashi

This book is a collection of articles by several leading experts in computational fluid dynamics and covers a broad range of topics in numerical methods in viscous flows. As designed by the editor, the various authors have written articles on topics that have been the centre of their own research. Most of the articles are short, typically 50 pages or so long and describe the author's experiences in perspective with related works of others. I would like to congratulate the editor for assembling such a distinguished set of researchers and organizing their reviews in a coherent style. The articles are well written and reasonably extensive. Upon reading the book, my impression was that the book serves a useful purpose of providing information to many secors of readers in various disciplines of industry and academia. The articles in the book are very interesting and cover topics such as parabolized NS equations, multigrids, hermitian methods, finite elements, shock/boundary layer interactions, turbulent flows with solid/fluid interactions, etc.

While the book is of much practical use, it is necessary to point out that it does not give enough details on any one method to the extent that a user can start programming and adapting the method to his problem. Because of this, the user can only note the theory and should then either refer to the bibliography or construct his own steps in the procedure, both of which are cumbersome and can be frustrating. Personally, I would have liked to see a volume with complete details but with less number of articles, similar to a collection of a few monographs in one book. Such a book will be unique in style as well as content and will differ from traditional review articles. Perhaps the editors may consider this for future publications. In spite of this, I recommend this book for practicing CFD researchers and engineers.

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