Drop coalescence and deposition in turbulent wet steam pipe flows

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The numerical turbulent coalescence/deposition model of Crane and Williams has been used to indicate likely trends in the development of drop size distribution and entrained water flow rate in the cross-over pipes of a nuclear wet steam turbine. Large increases in mean drop diameter have been shown to be possible, the results being very sensitive to the width of the initial size distribution, the entrained wetness fraction and the turbulence intensity. Deposition rate was also found to be strongly dependent on turbulence intensity, but inertial deposition onto and re-entrainment from the turning vanes of a bend did not significantly influence subsequent coalescence and turbulent deposition rates in the single example computed

Key words: *steam turbines, two phase flow, drop coalescence*

Problems caused by the two-phase (vapour/droplet) nature of the flow in condensing steam turbines have attracted considerable attention for many decades. Much of the experimental and theoretical work directed towards a better understanding of erosion and loss of efficiency has been reviewed in Ref 1. Wet steam at subatmospheric pressure has been the main area of interest, and substantial progress is now being made in the development of prediction techniques directly applicable in turbine design (see for example Refs 2 and 3), but the widespread introduction of water-cooled nuclear reactors has focused attention on higher pressures. With saturated steam at pressures up to about 70 bar supplied at the turbine stop valve, condensation occurs in the high-pressure cylinder, where the wet steam can no longer be classified as a dilute two-phase mixture and the vapour phase cannot be approximated as an ideal gas. Prediction of condensation and its effects in high-pressure turbines represents a more challenging problem than at low pressure (see for example Ref 4).

Among the mechanical, rather than thermal, aspects of wet steam behaviour at high pressures, deposition of drops onto blade surfaces is important in determining both the quantity of water which can be extracted from the flow within the turbine and the subsequent progress of condensation. Another aspect, which is not thought to be significant in low-pressure turbines, is drop coalescence in the flow; average inter-drop spacings of order 10 drop diameters, compared with values of order 100 at low pressures with similar wetness fraction (liquid phase mass fraction), ensure a much higher probability of drop collisions, as a result of accelerations, turbulence etc. The extent of coalescence will clearly affect deposition rates and further condensation by reducing the available liquid surface area. Calculations by Hedbäck[5] of drop size during spontaneous condensation in a nozzle at high pressure have shown better agreement with experiment when account was taken of coalescence, resulting from the drops' differing inertial responses to the rapid streamwise acceleration. Filippov and Daskal[6] have also carried out one-dimensional calculations on the same coalescence mechanism, turbulence again being neglected, for blade rows in a high-pressure turbine, and predict significant changes in drop size distributions.

One region of a nuclear wet steam turbine set is more amenable to a theoretical treatment of deposition and coalescence processes than the cylinders themselves. This is the pipework connecting the high-pressure cylinder exhausts to the external moisture separators and reheaters. Very little experimental information is available on the behaviour of the moisture in this region. Crane[7] has discussed various aspects of the two-phase flow in such 'cross-over pipes' and suggested that these processes could make a considerable contribution to water separation before the flow reaches the purpose-built separators, such as cyclone or chevron-plate types, which are intended to improve the efficiency of the steam-to-steam reheating and prevent excessive wetness fractions in the low-pressure cylinders. Improved understanding of the flow in these pipes will allow an assessment to be made of the extent to which moisture separator performance depends on the cross-over pipe layout, and could also lead to design changes for enhancing the overall separation efficiency.

Williams and Crane[8] solved the coagulation equations, describing the change in drop number concentration with time, for cross-over pipe steam conditions using existing theories[9,10] for coalescence due to turbulence. Although the regions of applicability were extremely limited, the predicted changes in drop size distribution were sufficiently large to encourage the development of a more comprehensive theory. In this paper, the recent turbulent co-

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alescence and deposition theory of Crane and Williams[11,12] is applied to cross-over pipe flows to predict the changes in entrained liquid flow rate and drop size distribution.

Turbulent coalescence and deposition theory

The coalescence model[11] may be considered as a combination of three components:

(1) An expression is derived for C_{12}, the collision coefficient between drops of diameter d_1 and d_2, such that $N_1N_2C_{12}$ is the number of collisions in unit time per unit volume where N_1 and N_2 are the respective number concentrations. This comes from an analysis of the relative motion of two drops in a turbulent vapour; it covers the whole range of drop size and turbulence intensity between the earlier collision theories of Saffman and Turner[9], for small drops in weak turbulence which have closely-correlated velocities on approach to a collision, and Abrahamson[10], for large drops in intense turbulence which have completely independent approach velocities. C_{12} is mainly a function of θ_1 and θ_2, the dimensionless relaxation times of the two drops; θ is defined as $u'\tau/L$ where τ is the relaxation time, u' the rms fluctuating velocity of the vapour (isotropic turbulence being assumed), and L the longitudinal integral length scale of the turbulence. The most restrictive assumption is that the fluctuating part of the relative motion between drops and vapour is in the Stokes regime, which limits drop diameters to the region below about 100 μm in the present application.

(2) A numerical method is used to solve the coagulation equations, the set of coupled, non-linear equations for the rate of change of N for each discrete size class in the logarithmic classification system. The scheme for assigning agglomerates to a size class ensures strict conservation of mass. In this part of the model, the chief assumption is that every collision results in a single, stable drop. Experimental work of the type which could determine the validity of this assumption has not yet covered the appropriate range of drop size and approach velocity. Although the Weber numbers of the largest drops expected in this context are sufficiently low to prevent break-up after coalescence, based on such experiments as those of Brazier-Smith *et al*[13], the probability of bouncing, instead of coalescence, cannot yet be estimated.

(3) The pipe is divided axially and radially into a number of annular cells, the flow being assumed axisymmetric. Within each cell, the coagulation equations are solved over an interval equal to the time taken to traverse the cell at the local axial mean velocity, with no mean slip between vapour and drop velocities in this direction. The local mean velocities $\bar{u}$, also u' and L, are specified initially for every cell, based on empirical data or measurements etc, and the solution is obtained by marching along the pipe in the streamwise direction. The calculated radial concentration gradients are used to evaluate the radial flux of drops between cells and an expression for deposition probability within the viscous sublayer allows calculation of the deposition rate on the wall[12], for the turbulent impaction mechanism only. Sufficient drainage points in the pipe are assumed so that the films or rivulets of deposited water never develop sufficiently to cause significant re-entrainment.

Results from the combined model must be viewed with caution at the extreme ends of the drop size spectra. Collisions between two small drops, of order 1 μm, will be influenced by the small scales of turbulent motion, not considered here, although the evolution of a polydisperse spectrum will be controlled largely by collisions between very differently sized drops, for which the present theory is valid. Also, the turbulent shear collision mechanism[9,11] may become important at small sizes. Deposition rates will be underestimated for the smallest drops ($d < 3$ μm approximately, for the present application) which fall in the so-called diffusion-impaction regime of turbulent deposition[12]. Where the underestimate becomes significant, however, deposition rates predicted by theories valid for that regime are themselves smaller than those for drops in the impaction regime ($d > 3$ μm). It may be shown[14] that gravity, also neglected, will not strongly influence the collision process for drops up to about 100 μm in diameter under cross-over pipe conditions, fortunately coinciding with the approximate limit for validity of Stokes' law for the fluctuating relative motion. Gravitational effects on deposition in a horizontal pipe section will of course modify the results to be presented here.

Notation

d	Drop diameter
D	Pipe diameter
L	Longitudinal integral length scale of turbulence
$\dot{m}$	Mass flow rate
N	Drop number concentration (number per unit volume)
n	Drop number density (number in a size class ÷ size range of that class, $\approx dN/dd$)
p	Pressure
r	Radial co-ordinate (from pipe axis)
u_b	Bulk velocity
$\bar{u}$	Local mean velocity in x-direction
u'	Local fluctuating velocity (such that instantaneous velocity $u = \bar{u} + u'$)
u_*	Friction velocity
x	Axial co-ordinate (from pipe entry)
y	Entrained wetness fraction (mass of drops per unit mass of wet steam)

Subscripts

0	at $x = 0$
32	Sauter mean
∞	for whole size distribution
fd	in fully-developed flow
l	entrained liquid

Abbreviations

SMD	Sauter mean diameter
uldf	Upper limit distribution function

While considerable confidence may be placed in predictions made from the first or second parts of the model in isolation, the performance of the combined model is much more uncertain. An attempt at verification of the complete model[11,12,14,15], in the absence of any suitable existing experimental data, gave qualitative agreement; pending the development of improved techniques to reduce the large experimental uncertainties, applications of the model should be regarded as giving an indication of trends and orders of magnitude rather than precise predictions.

Cases computed

As a datum case, a typical cross-over pipe of diameter $D = 1000$ mm has been taken, conveying steam with wetness fraction $y = 10\%$ and absolute pressure $p = 10$ bar at a bulk velocity u_b of 50 m/s. Radial variation of the mean velocity $\bar{u}$ and of the turbulence parameters u' and L was assumed to correspond to fully-developed flow, as given by Lawn[16]. u' rises from $0.95u_*$ on the centreline to $2.00u_*$ at $2r/D = 0.9$, where u_* is the friction velocity and r the radial coordinate: L is close to $0.5D$ in the core flow and falls to about $0.35D$ at $2r/D = 0.9$.

The initial size distribution of the entrained drops was described by the upper-limit distribution function, originally proposed by Mugele and Evans[17] and discussed in the context of wet stream by Ow and Crane[18]. Setting both the skewness and polydispersity parameters of the distribution to unity[18], the number density n d is given by:

$$n = K(d_m/[d^4(d_m - d)]) \exp\{-w^2\}$$

where K is a constant, d_m is the maximum diameter (resulting from a break-up process governed by a critical Weber number) and $w = \ln$ $d/(d_m - d)$. The mass median diameter of such a distribution is $d_m/2$. This was considered to be a reasonable representation of spectrum shape for the so-called 'coarse water', that part of the total steam-borne water which has been re-entrained from blade surfaces in the high-presure turbine; if critical Weber numbers deduced from experiments in low-pressuree steam are applicable here, then d_m would be order 10 μm. It is generally believed (eg Gyarmathy[1]) that the remainder of the drops, fog drops which since nucleation have passed through all blade rows without being deposited, fall within the same size range, so that this upper-limit distribution might be taken to include all the drops in the flow. In the absence of sufficient data, further consideration of this matter has been restricted to a computation in which the input upper-limit distribution was modified by increasing the number of drops with $d = 2$ μm, representing fog drops, so that their mass formed 50% of the total liquid mass. (In practice, multimodal mass frequency distributions are likely, on evidence such as the measurements in Ref 19.) Values of d_m from 5 μm to 40 μm were considered, the data being supplied in the form of a ten-element histogram which was converted by the computer program to the required logarithmic histogram form with up to 25 elements.

The grid defining the annular cells was chosen to give five concentric cells in the pipe cross-section, each having the same cross-sectional area. The number of cells in the radial direction affects deposition more than coalescence, and this choice was made to provide a good prediction of deposition rate, based on earlier experience[12], while minimizing computer time. The sensitivity of both coalescence and deposition to axial cell length was small, bearing in mind the variations caused by uncertainty in turbulence parameters etc, and a value of $D/15$ was selected for most computations.

The sensitivity of the solutions to pressure, entrained wetness fraction and turbulence parameters was examined, and finally the influence of a single bend in the pipe was investigated. A 90° mitre bend with ten circular-arc turning vanes was considered, positioned eight pipe diameters from the inlet. Calculation of inertial deposition on turning vanes was made by a two-dimensional version of the program described in Ref 20; deviations from Stokes' drag law for the mean relative motion are important in this situation, and were included in the calculation. The assumption of another upper-limit distribution for water re-entrained from the vane trailing edges, taken to be homogeneous over the pipe cross-section, allowed a new combined size distribution to be used as the starting point for coalescence/deposition prediction downstream of the bend. The maximum diameter of re-entrained drops was given by a critical Weber number of 50, based on the correlation of Stastny[21].

Results and discussion

Unless steam conditions etc. are specifically mentioned in this section or in the figure captions, the results refer to the datum case, ie $D = 1000$ mm, $p = 10$ bar, $u_b = 50$ m/s, $y_0 = 10\%$, fully-developed profiles of $\bar{u}$, u' and L as described earlier.

The separate and combined effects of coalescence and deposition are illustrated in Fig 1, showing the change in number density distribution over a straight length of twenty pipe diameters. Coalescence is seen to be considerably more effective than deposition in reducing the number of drops, although its effect is slightly smaller when both processes are included in the computation. This occurs because the extent of coalesence depends heavily on the numbers of very large drops, which quickly absorb the small drops; deposition, by reducing the number of large drops present, retards the coalescence process.

In Fig 2(a), the change in the distribution of drop flow rate by size class is compared for initial spectra having maximum diameters of 10 μm and 40 μm. The strong influence of the larger drops is again evident. The corresponding cumulative mass distributions, for an initial d_m of 10 μm, are shown in Fig 2(b), which also includes the result of simulating an input distribution with 50% of the total mass in 2 μm fog drops. (Conversion to logarithmic form smears the input distribution so that the starting distribution for the calculation has a mass median diameter of 2.6 μm, compared with 5 μm for the unmodified uldf). By $x/D = 20$, the effect of the additional fog has been to reduce the maximum size quite considerably, although the mass median diameter has still increased by a factor of about five.

From Fig 3, it can be seen that evolution of the size distribution, as measured by the Sauter mean diameter (SMD) d_{32}, is negligible for an initial d_m of 5 μm. A quadrupling of SMD occurs for $d_m =$ 10 μm; increases in initial d_m beyond 20 μm have little additional effect, the largest drops being present only in very small numbers. Also plotted is a result

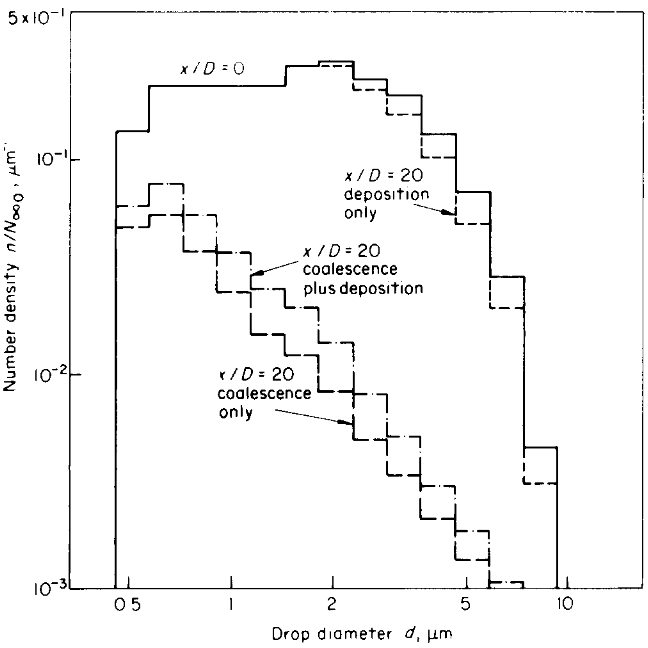

Fig 1 Comparison of the effects of coalescence and deposition on number density distribution

obtained by assuming that only half the collisions produce a single combined drop (the other half being bounces with no interchange of mass or else immediate fractures into two drops identical to those from which the unstable agglomerate was formed.) In practice, coalescence efficiency will be a function of the drop sizes, as well as impact angle and velocity, but this simplified example indicates the importance of obtaining more experimental data. The radial variation of SMD (Fig 4) is small but not negligible. Larger, circumferentially non-uniform variations might be found in practice, caused by the effects of gravity, re-entrainment, flow in bends etc.

The flow rate of entrained liquid, as a fraction of its initial value, is plotted in Fig 5, showing that the rates of deposition are broadly similar for all the size distributions having d_m initially 10 μm or above. This is consistent with most work on deposition in the turbulent impaction regime[12], which implies a rather flat curve of deposition rate *versus* particle size over a range which covers $3\ \mu m < d \leqslant 60\ \mu m$ in the present application. Suppression of coalescence has a relatively small effect, while the initial wetness fraction affects the result only through its influence on coalescence. To illustrate the underestimate of deposition for small drop sizes, the points marked by squares on Fig 5 have been calculated for a uldf with $d_m = 5$ μm using the equations recommended by McCoy and Hanratty[22] and Wood[23] for both the diffusion-impaction and the impaction regimes, assuming smooth pipe walls. Estimates using these equations are also shown for $d_m = 10$ and 40 μm. Satisfactory agreement is obtained except from Wood's equation for $d_m = 40$ μm; for drops larger than 11 μm, this equation, which is based on theory

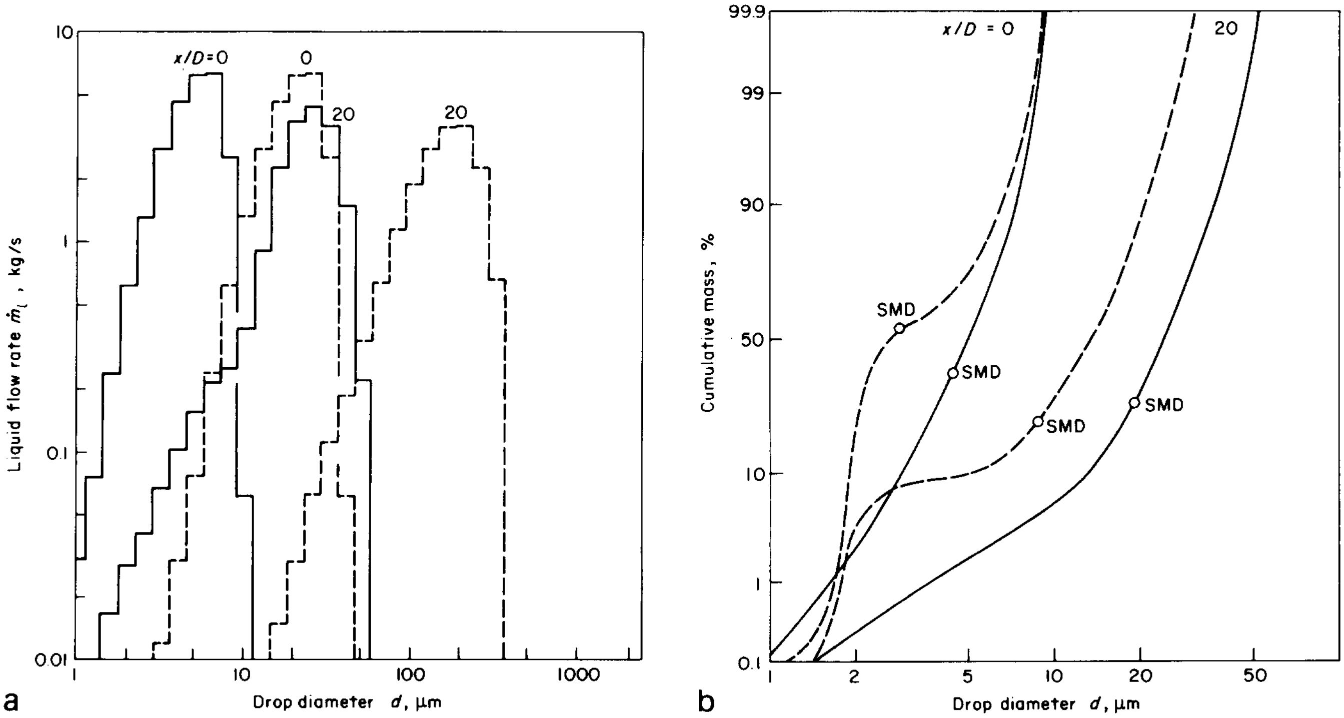

Fig 2 Evolution of size distributions (cross-section averages) over a pipe length of 20 diameters: (a) Liquid mass flow rates in each size class for initial $d_m = 10$ *μm (solid line) and 40 μm (broken line)*

(b) Cumulative mass distributions for initial $d_m = 10$ *μm: solid lines—uldf at* $x/D = 0$ *and result at* $x/D = 20$*; broken lines—uldf with additional 2 μm drops at* $x/D = 0$ *and result at* $x/D = 20$

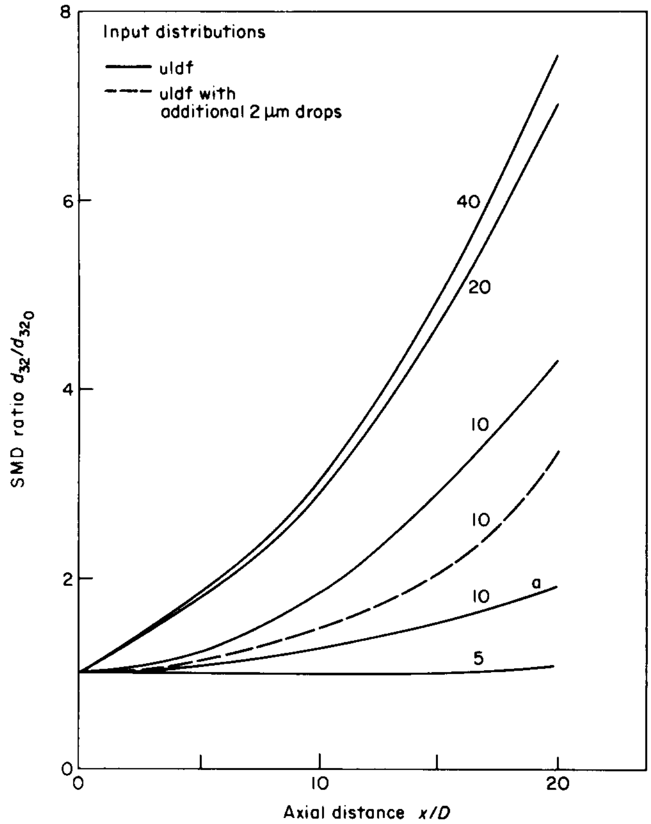

Fig 3 Effect of initial d_m *on increase in Sauter mean diameter* d_{32} *(cross-section average). Numbers on curves denote* d_m *(μm) at* $x = 0$*. Curve (a): coalescence efficiency = 50% (independent of drop sizes)*

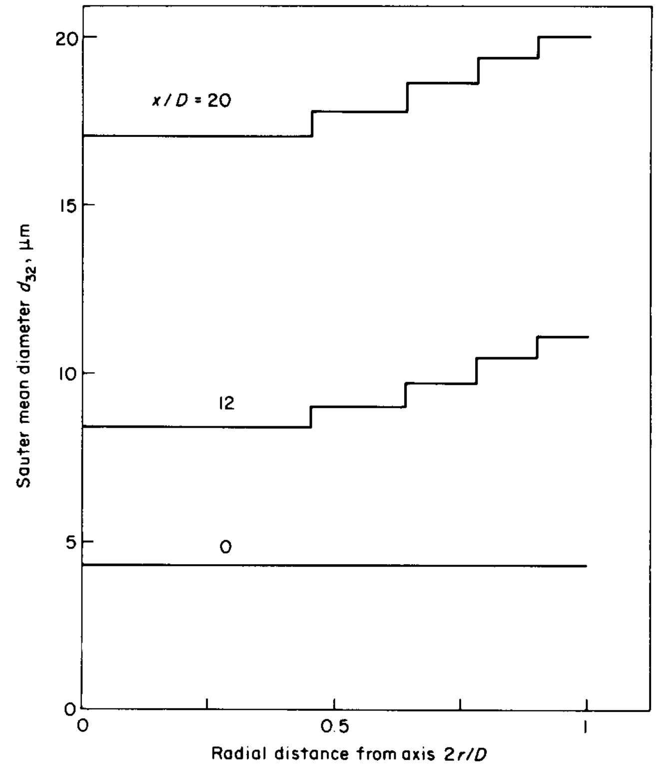

Fig 4 Radial variation of Sauter mean diameter, for initial $d_m = 10$ *μm*

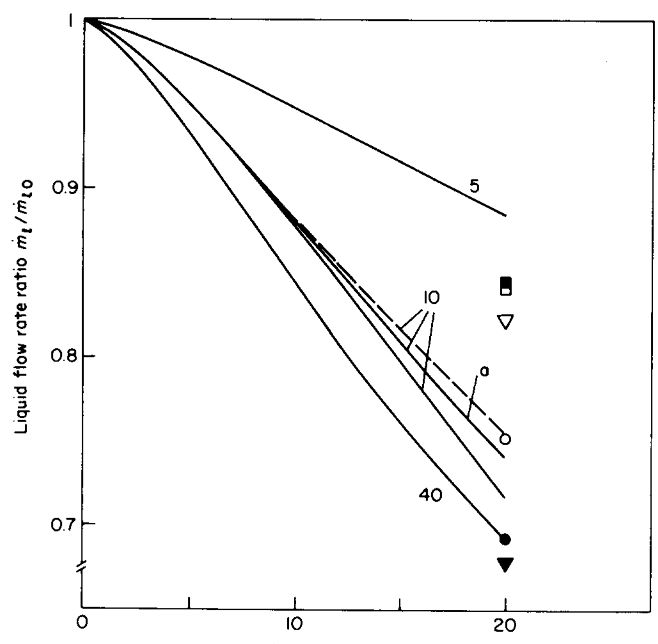

Fig 5 Effect of turbulent deposition on entrained liquid flow rate. Numbers on curves denote d_m *(μm) at* $x = 0$*. Processes included in calculation are coalescence and deposition, except the broken line which is for deposition only. Curve (a):* $y = 4\%$ *at* $x = 0$*. Estimates from correlations recommended in McCoy and Hanratty[22] (solid symbols) and Wood[23] (open symbols): initial* $d_m = 5$ *μm* ■□, *10 μm* ●○, *40 μm* ▼▽

only, predicts a reduction in deposition rate with increasing drop size, whereas the data correlation[22] suggests a constant rate for all sizes in this uldf. It should be mentioned here that the rates of turbulent deposition in straight pipe sections which were presented in Ref 7 are now believed to have been over-estimated, in the light of more recent work on the impaction regime. However, the total deposition in a hypothetical pipe with four radiused bends (no turning vanes) was found[7] to be dominated by inertial deposits on the bend outer walls for large drops (40 μm). The shift in size distribution predicted by the coalescence model will enhance this effect, so strengthening the broad conclusions[7] that the bulk of the moisture separation could occur prior to the separator vessel.

Predictions of the influence of turbulence intensity and scale are shown in Fig 6. Halving the length scale has a noticeable effect on both coalescence and deposition, but the effects of changes in intensity are much larger; fluctuating velocities twice those in fully-developed flow cause the changes over twenty pipe diameters in the datum case to occur in only about eight diameters. Values of u' less than in fully-developed flow are unlikely in a cross-over pipe, because of the effects of the moving blade rows in the high-pressure turbine. In Fig 6 curves (a) correspond to intensities $u'/\bar{u}$ of about 3% and 7% at radii $2r/D = 0$ and 0.95 respectively, and curves (c) to twice these values. Artificially increasing the levels of turbulence might offer a means of enhancing the formation of large drops and so improving moisture separation efficiency.

The initial entrained wetness fraction, and hence drop concentration, will clearly have a strong effect on coalescence. It can be seen from Fig 7 that very little increase in SMD occurs when the drops represent only 4% of the total (liquid + vapour) mass. Prediction of coalescence thus depends heavily on a knowledge of the distribution of the liquid between steam-borne drops and wall films etc at the starting point of the computation. Lowering the pressure to 6 bar reduces the rate of coalescence, as expected, if the mean velocities are unchanged; however, if the bulk velocity is simultaneously raised to maintain the same mass flow rate as at the higher pressure, the effect of the reduced drop concentration is more than counterbalanced by the increased fluctuating velocity component, resulting in slightly increased rates of coalescence. A further expected increase (curve f) occurs when the lower turbine exhaust pressure is coupled with a high wetness fraction, as would occur in practice. If a smaller pipe is used to convey the same flow, coalescence is again increased as a result of higher fluctuating velocities, notwithstanding the reduction in residence time caused by the increased mean velocities. (u_b is the same for curves (e) and (g).)

The results presented in Fig 8 illustrate the effect of one particular type of bend at an arbitrarily chosen location in the pipe. A more thorough study

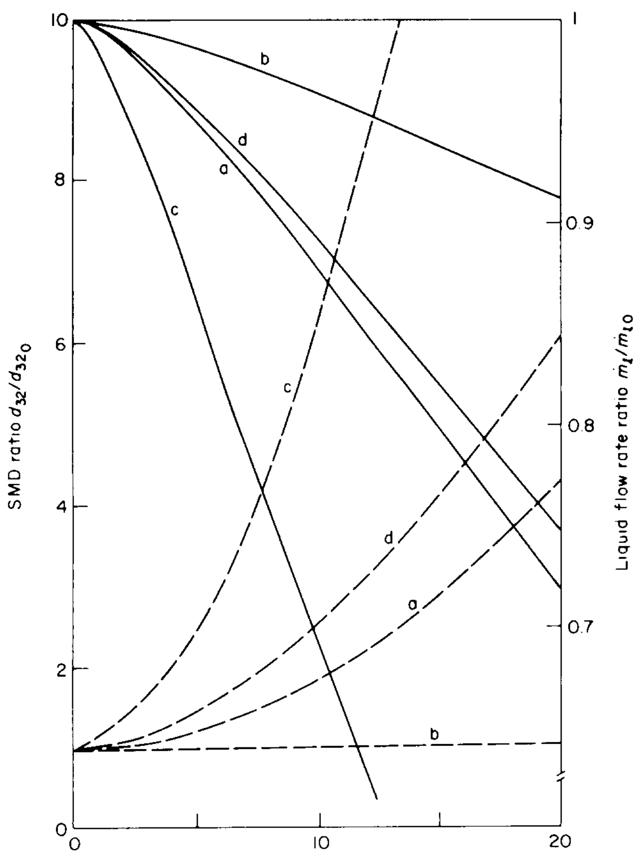

Fig 6 Effect of turbulence intensity and length scale on reduction in entrained liquid flow rate (solid line) and increase in cross-section average Sauter mean diameter (broken line), for initial $d_m = 10\,\mu m$. *(a)* $u' = u'_{fd}$; $L = L_{fd}$ *(b)* $u' = \frac{1}{2}u'_{fd}$; $L = L_{fd}$ *(c)* $u' = 2u'_{fd}$, $L = L_{fd}$ *(d)* $u' = u'_{fd}$; $L = \frac{1}{2}L_{fd}$

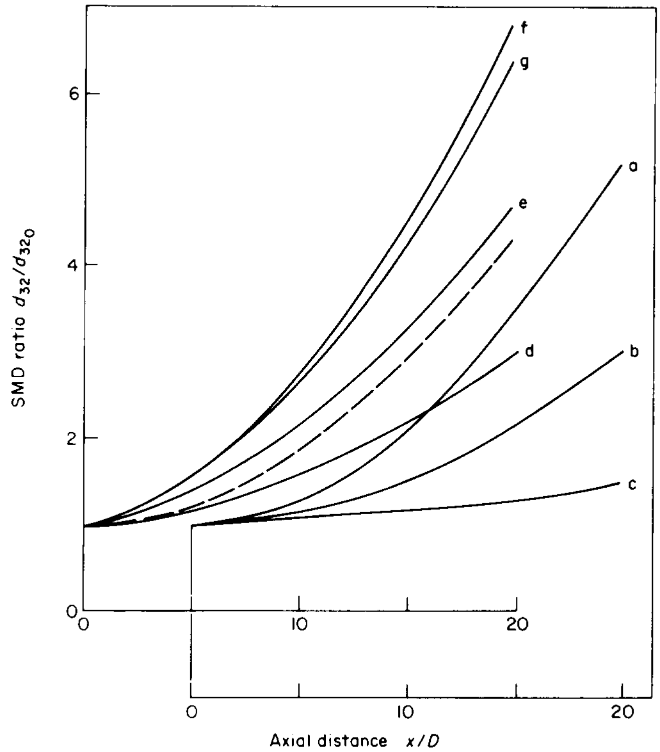

Fig 7 Effect of flow conditions on increase in Sauter mean diameter (cross-section average), for initial $d_m = 10\,\mu m$ *(initial* $d_{32} = 4.37\,\mu m$*). The datum case is given by the broken line. Variations from datum case: (a), (b), (c) initial* $y = 12\%$, *8% and 4% respectively with datum* u_b *(d)* $p = 6$ *bar with datum* u_b *(e)* $p = 6$ *bar with datum* $\dot{m}$ *(f)* $p = 6$ *bar and initial* $y = 13\%$ *with datum* $\dot{m}$ *(g)* $D = 785$ *mm with datum* $\dot{m}$

of bend effects is hardly warranted unless a specific turbine set is under investigation. (However, an estimate of deposition only in a hypothetical pipe with four radiused bends has been given[7].) Fig 8(a) shows that over 80% of 10 μm drops pass through the turning vanes, but all drops larger than 100 μm are captured. (As pressure is reduced, the extent to which the capture efficiency of the bend will increase is illustrated by comparison with Fig. 4 of Ref 7.) Assuming that all captured water is re-entrained, which will not necessarily apply to vanes having a vertical span, the drop size distributions after complete break-up of re-entrained water, assumed to occur within a small distance from the bend, and at $x/D = 20$ are as shown in Fig 8(b). The maximum size present is now 150 μm, compared with 50 μm upstream of the bend; at lower pressures, even larger drops would be formed. The SMD, however, jumps only from 6.9 to 7.3 μm, and between the bend ($x/D = 8$) and $x/D = 20$, with unchanged turbulence parameters, the increase in SMD and reduction in $\dot{m}_l$ differ only marginally from those computed in the absence of a bend; the number of very large 'secondary drops' has not had sufficient time to build up to a level where it can exert a significant influence on the rate of coalescence. The effective length scale of the turbulence will be reduced immediately downstream of the bend, and this could enhance subsequent coalescence and deposition.

Wall roughness effects are not included in the model. While roughness can produce very large increases in deposition in the diffusion-impaction regime[23], there are insufficient data to test the expressions which have been put forward for predicting deposition to rough surfaces. Calculations[23] suggest that in the impaction regime, referred to by Wood as the 'particle inertia-moderated regime', the effect is less marked. Even so, use of his expressions for the present datum case with initial $d_m = 10$ μm and an equivalent sand grain roughness height of 25 μm, leads to an entrained liquid flow rate at $x/D = 20$ of only 54% of that at $x/D = 0$, compared with 75% for smooth walls. No information is available regarding the effect of roughness on coalescence, but as a first approximation the present model could be used with appropriate increases in the specified fluctuating velocities for the vapour phase, eg making all u' proportional to u_* and using well-established relationships for the effect of roughness on u_*.

Gravitational effects in horizontal pipe sections cannot be included in the axisymmetric model, but may be put in context by noting that the terminal velocity of drops up to about 30 μm, in the datum case, will be less than 10% of the turbulent deposition velocity (ie number of drops deposited on unit area in unit time divided by mean concentration in the bulk flow), and these two velocities will become roughly equal for 90 μm drops. (Effective terminal velocities may be considerably reduced by the turbulence[24].) Asymmetry of the drop concentration profile in a horizontal section of cross-over pipe was discussed briefly elsewhere[7].

A further coalescence mechanism which is being investigated at present is that occurring in pipe bends, caused by different centripetal acceleration of differently sized drops. It should be possible to combine the centrifugal and turbulent mechanisms in the program, with the simplifying assumptions that they may be superimposed and that axial symmetry of drop concentration is maintained.

Conclusions

Application of the numerical model to typical cross-over pipe flows has shown that turbulent coalescence can have very large effects on the drop size distribution of the wet steam. Increases in Sauter mean diameter by factors as high as seven were predicted over a length of twenty pipe diameters in fully-developed flow, for initial distributions with maximum diameter 20 μm or more, while very little coalescence occurred for an initial maximum of 5 μm. The effects were very sensitive also to the entrained wetness fraction, with a rather low coalescence rate for only 4% wetness, and to the fluctuating velocity components. Doubling the turbulence intensities from those in fully-developed pipe flow roughly halved the length of pipe needed for a given increase in mean diameter, but the results were much less dependent on the length scale of the turbulence.

Computed turbulent deposition rates were, for fully-developed flows, in generally satisfactory agreement with predictions using the expressions of McCoy and Hanratty[22], but were also found to depend strongly on turbulence intensity, a result not obtainable from earlier deposition theories. Coalescence exerted a relatively weak influence on deposition, the drop sizes falling mostly in the range where deposition rates do not depend strongly on size. Deposition onto and re-entrainment from the turning vanes of a bend altered the drop size distribution to an extent that was not sufficient for significant modification of the rates of coalescence and deposition downstream of the bend, although this is not necessarily a typical result.

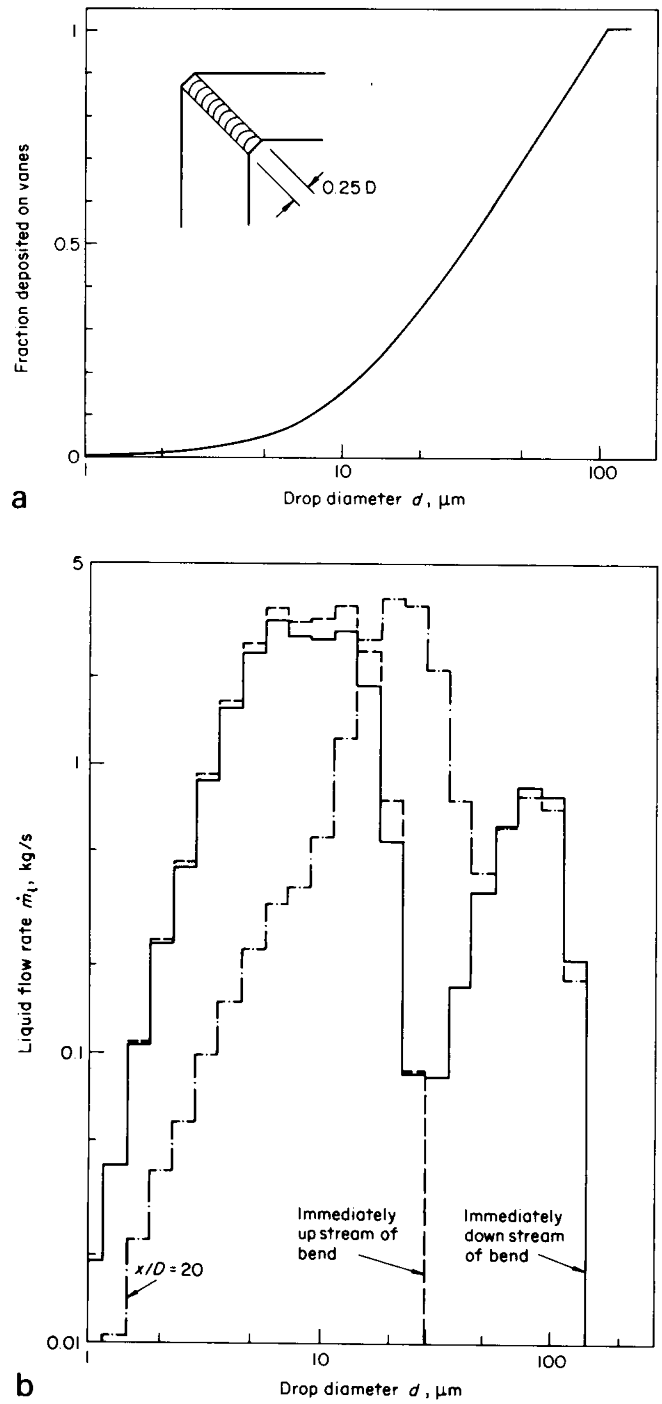

Fig 8 Effect of a 90° bend at x/D = 8 on the size distribution, for initial $d_m = 10$ μm (a) Fraction of drops deposited on turning vanes as a function of drop size (b) Liquid mass flow rates in each size class

In addition to experimental work necessary for improved verification of the theoretical model, in particular determination of coalescence efficiencies, two major uncertainties should be resolved before the model can be applied reliably to a particular wet steam pipe flow: the fraction of the liquid phase which is initially contained in steam-borne drops, and the turbulence intensities throughout the pipe.

Acknowledgement

The contribution of Dr. J. J. E. Williams in developing the numerical model for turbulent coalescence and deposition is gratefully acknowledged. Some of the results presented here were first derived by him[14], with certain differences in steam conditions. (An error in reference 14 in specifying the histogram approximation to the uldf has been corrected here.)

References

1. **Moore M. J. and Sieverding C. H. (editors)** Two-phase Steam Flow in Turbines and Separators. *Hemisphere, Washington, 1976*
2. **Kreitmeier F., Schlachter W. and Smutny J.** An investigation of flow in a low-pressure wet steam model turbine and its use for determining wetness loss. *Paper C178/79, Instn. Mech. Engrs. Conf. 'Steam Turbines for the 1980s', London, 1979*
3. **Pollard D., Lord M. J. and Stockton E. C.** An evaluation of low pressure steam turbine blade erosion, *Paper C259/79, Instn. Mech. Engrs. Conf. 'Steam Turbines for the 1980s', London, 1979*
4. **Bakhtar, F. and Ghassemi B.** A study of nucleating and wet steam flows in high pressure steam turbines. *Paper C191/79, Instn. Mech. Engrs. Conf. 'Steam turbines for the 1980s', London, 1979*
5. **Hedbäck A. J. W.** Das Verhalten der Zustandsgleichung IFC-1967 bei unterkühlten Zuständen des Wasserdampfes. *VDI-Berichte Nr. 361, 1980*
6. **Filippov G. A. and Daskal Yu. I.** The process of interaction of particles in two-phase flows'. *Teploenergetika 1978,* **25***(10), 79–80. English translation: Thermal Engineering,* **25***(10), 67–69*
7. **Crane R. I.** Some aspects of wet steam flow in turbine cross-over pipes. *Int. J. Mech. Sci., 1978,* **20**, *237–246*
8. **Williams J. J. E. and Crane R. I.** Drop coagulation in cross-over pipe flows of wet steam. *J. Mech. Engng. Sci., 1979,* **21**, *357–360*
9. **Saffman P. G. and Turner J. S.** On the collision of drops in turbulent clouds. *J. Fluid Mech., 1956,* **1**, *16–30*
10. **Abrahamson J.** Collision rates of small particles in a vigorously turbulent fluid. *Chem. Eng. Sci., 1975,* **30**, *1371–1379*
11. **Crane R. I. and Williams J. J. E.** A general model of turbulent coagulation in two-phase pipe flow. *Paper C85/81, Instn. Mech. Engrs. Conf. 'Gas-Borne Particles', Oxford, 1981*
12. **Williams J. J. E. and Crane R. I.** Deposition of large particles from turbulent flow in pipes. *Paper C86/81, Inst. Mech. Engrs. Conf. "Gas-Borne Particles', Oxford, 1981*
13. **Brazier-Smith P. R., Jennings S. G. and Latham J.** The interaction of falling water drops: coalescence. *Proc. Roy. Soc. Lond., 1972,* **A326**, *393–408*
14. **Williams J. J. E.** Droplet coagulation in two-phase turbulent pipe flows. *Ph.D. Thesis, London. Univ. 1980*
15. **Ow C. S.** Studies of two-phase turbulent pipe flow. *Ph.D. Thesis, London. Univ. 1980*
16. **Lawn C. J.** The determination of rate of dissipation in turbulent pipe flow. *J. Fluid Mech., 1971,* **48**, *477–505 (Also CEGB Rep. RD/B/R1575 parts A & C)*
17. **Mugele R. A. and Evans H. D.** Droplet size distributions in sprays. *Ind. Engng. Chem., 1951,* **43**, *1317–1324*
18. **Ow C. S. and Crane R. I.** On the critical Weber number for coarse water formation in steam turbines. *J. Mech. Engng. Sci., 1979,* **21**, *353–356*
19. **Dibelius G., Ederhof A. and Voss H.** Analysis of wet steam flow in turbines on the basis of measurements with a light scattering probe, in '*Two-phase momentum, heat and mass transfer in chemical, process and energy engineering systems', Vol. 1, ed. F. Durst et al., Hemisphere, Washington, 1979*
20. **Crane R. I. and Evans R. L.** Inertial deposition of particles in a bent pipe. *J. Aerosol Sci., 1977,* **8**, *161–170.*
21. **Stastny M.** Structure of secondary liquid phase downstream of moving blades in LP cylinder stages of steam turbine. *Paper C188/79, Instn. Mech. Engrs. Conf. 'Steam Turbines for the 1980s', London, 1979*
22. **McCoy D. D. and Hanratty T. J.** Rate of deposition of droplets in annular two-phase flow. *Int. J. Multiphase flow, 1977,* **3**, *319–331*
23. **Wood N. B.** The mass transfer of particles and acid vapour to cooled surfaces. *J. Inst. Energy, 1981,* **54**, *76–93. Also J. Aerosol Sci., 1981,* **12**, *275–290*
24. **Kubie J.** Settling velocity of droplets in turbulent flow. *Chem. Engng. Sci., 1980,* **35**, *1787–1793*

Note added in proof: Calculations similar to those in this paper have been made for comparison with measurements in the pipework of a European PWR turbine set. Results are confidential, but are probably unrepresentative of present day practice because of the low steam pressure.