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The effect of turbulence on the phase change of droplets and particles under non-equilibrium conditions

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Abstract—A model is developed for the description of the phase change process (sublimation or evaporation) of droplet and particles in a gaseous environment under turbulent flow. For this purpose the appropriate conservation and closure equations for the process are derived. Turbulence is simulated by suitably correlated Gaussian random numbers. The system of equations is solved numerically for the case when the mixture of the two phases is subjected to a step increase in the wall temperature. The Monte Carlo method is used to obtain the average quantities of interest in the flow field. The effects of several parameters (such as initial particle sizes, turbulence intensity and size of the wall temperature step) on the rate of change of the condensed phase are examined. Gas temperatures, velocities, distances and times required for the completion of the phase change are calculated and reported.

INTRODUCTION

HEAT TRANSFER in suspensions was first examined in the 1960s, when suspensions were considered as an alternative to high pressure gases for nuclear reactor cooling. The experimental studies of Farbar and his co-workers [1, 2], Tien and Quan [3] and Danziger [4], among others, provided the engineering correlations for the convective film coefficient of a suspension. A review of most of the experimental data and the resulting correlations can be found in Pfeffer *et al.* [5]. Regarding the analytical studies on the subject, Tien [6] made the first one for homogeneous suspensions of very low solids content. Ozbelge and Sommer [7], and Michaelides [8] developed later different analytical and computational models for the heat transfer of suspensions.

Regarding the heat transfer and evaporation of droplets, a substantial body of analytical results and experimental data were collected in the past because of the engineering interest in boilers and boiling water reactors. The experimental data were compiled in several correlations referring to particular two phase flow regimes. The works of Collier [9] and Rohsenow and Hartnett [10] summarize a great deal of the available information. Physical models for droplet flow in tubes appeared rather recently; among these Whalley *et al.* [11] examine the subject of water droplet flow in steam under hydrodynamic and thermodynamic non-equilibrium conditions. Use of the experimental data by Miropolskii *et al.* [12] is made extensively in this physical model. Gyarmathy [13] provided an extensive review and developed a general model for the flow of droplets in a carrier gaseous stream.

Michaelides and Lasek [14, 15] examined the flow and phase change of particles and droplets under conditions of thermodynamic and hydrodynamic non-equilibrium, when there is a temperature step at the wall or when hot particles are injected in a developed flow. The present study is essentially an extension of the last two: it extends the model developed before to two-dimensional duct flows where turbulence dominates the transport of particles and examines the response of evaporating droplets and particles to turbulent eddies. The behavior of particles or droplets in a gaseous stream (of the same or different substance) is studied, when the velocities and temperatures of the two phases are different (that is there is no thermodynamic or hydrodynamic equilibrium). Therefore, there is momentum, heat and mass transfer between the two phases, which results in higher rates of heat and mass transfer.

The turbulent velocity field is simulated by the use of suitably correlated random numbers obeying a Gaussian distribution function. Average quantities of

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NOMENCLATURE

c	specific heat
C_D	drag coefficient
D	pipe diameter
F_D	drag force
f	friction coefficient
g	gravity
h_{fg}	latent heat
h	heat transfer coefficient
k	eddy kinetic energy
l	eddy length scale
N	number of droplets/particles
P	pressure
Q	heat transfer
R_1, R_2	random numbers
Re	Reynolds number
T	temperature
t	time
U	longitudinal velocity
u^*	friction velocity
V	radial velocity
v_{fg}	volume change upon phase transformation.

Greek symbols

α	particle/droplet radius
δ	specific heat ratio
λ	turbulence modulation factor
μ	kinematic viscosity
ν	dynamic viscosity
ρ	density
σ	Stefan–Boltzmann constant
σ_u, σ_v	turbulence intensities
τ	characteristic time.

Subscripts

0	initial
D	refers to pipe diameter
e	eddy
g	gas
p	particles
w	wall.

Superscript

$'$	refers to fluctuations
$\cdot$	rate.

interest are obtained by the use of the Monte Carlo technique applied to a large number of individual particle trajectories.

THE SET OF EQUATIONS FOR A SUSPENSION

The flow of particles undergoing phase change in a duct is assumed to be two-dimensional with the model of particles continuously bouncing on the walls as described for isothermal flows in ref. [16]. For the simplicity of the calculations all particles are initially assumed to have the same size. However, the set of equations comprising the model covers the polydisperse suspensions and can be adjusted to take them into account with minor modifications. The diameter of the particles in all cases considered is assumed to be small ($2\alpha/D \ll 1$). The gas velocities and the Reynolds numbers considered are such that the flow is turbulent and the particles do not deposit on the walls of the duct. Particle or droplet concentration by volume is small, (less than 1%) thus ensuring negligible particle interactions. It must be pointed out that because of the high ratio of densities this assumption does not preclude high loadings (mass flow ratios). The conservation equations for such a fluid were derived in [15] and [17]. These equations are summarized here as follows.

Continuity equation

A combined time-averaged equation for the conservation of the mass of the suspension may be written in terms of the number and size of particles (or droplets) as follows:

$$N\frac{4}{3}\pi\rho_p\left(\alpha^3\frac{d\bar{U}_p}{dt}+3\bar{U}_p\alpha^2\frac{d\alpha}{dt}\right)+\rho_g\frac{d\bar{U}_g}{dt}+\frac{d\rho_g}{dt}\bar{U}_g=0 \quad (1)$$

where N is the number density of the particles (particles per m^3), $\bar{U}$ is the time-average local longitudinal velocity, ρ the density (which is assumed free of time fluctuations), α the instantaneous radius of the particles (variable because of the change of phase). The subscripts p and g refer to the particles and the gas, respectively. Droplets and particles are relatively rigid and for this reason the density of the particles is assumed to be constant. The density of the gaseous phase is given as a function of its pressure, temperature and composition.

The momentum equations for the two phases

The momentum equation may be written as a force balance on a particle of radius α as follows:

$$\frac{4}{3}\pi\rho_p\frac{d}{dt}(\alpha^3U_p)=F_D-\frac{4}{3}\pi\alpha^3\,\mathrm{grad}\,P+\frac{2}{3}\pi\alpha^3\rho_g\left(\frac{dU_g}{dt}-\frac{dU_p}{dt}\right)+6(\pi\nu)^{0.5}\alpha^2\rho_g\int_0^t\frac{\frac{dU_g}{dt}-\frac{dU_p}{dt}}{(t-t')^{0.5}}dt'+\frac{4}{3}\pi\alpha^3g(\rho_p-\rho_g), \quad (2)$$

where the bold letters represent vectorial quantities, $\boldsymbol{g}$ is the acceleration due to the gravity and v the dynamic viscosity of the gas.

The left-hand side of the above equation represents the instantaneous change of momentum of the particle. The first term on the right-hand side represents the drag force. The second term is due to the pressure gradient; this term is negligible, unless the particles are in the presence of very strong pressure gradients, a case never met in duct flows [13]. The third term is due to the added mass of the particles because of the acceleration of a small quantity of gas with it. This term is of importance when the density of the gas is comparable to or higher than that of the particles. In the cases examined here $\rho_p/\rho_g \gg 1$ and the added mass term is neglected also. The fourth term represents the so called Basset force, which is due to the history of the acceleration of the particles. The Basset force may become important when the particles are in the submicron range. The effect of this force in the case of particle sublimation was examined in ref. [14] and found to be negligible for the applications considered here. For this reason this term was neglected in the calculations that follow. Finally, the last term represents the action of the gravity forces on the particles.

The viscous drag force F_D is given by an empirical relation in terms of the relative velocity of the particles as follows:

$$F_D = \tfrac{1}{2}C_D\pi\alpha^2\rho_g|U_g - U_p|(U_g - U_p), \qquad (3)$$

where C_D is the drag coefficient, a known function of the Reynolds number of the particles [15–17].

The momentum equation for the gas is used in the form of the pressure drop equation in the longitudinal direction. The usual assumption for duct flows is employed here that the radial component of the pressure gradient is negligible in comparison to the other forces. The friction coefficient for this flow is obtained from a semiempirical model developed in ref. [16] which reads as follows:

$$f = f_0 + 0.072m^*\frac{(Dg)^{0.5}}{\bar{U}_g} \qquad (4)$$

where m^* is the loading of particles (ratio of condensed phase to gaseous mass fluxes) and f_0 is the friction factor for the gaseous phase flowing alone in the duct.

The heat transfer and energy equations

Evaporation of the particles occurs because of the heat transfer from the gas to the particles or from the hot walls of the duct to the particles. Convection is the predominant mode of heat transfer from the gas to the particles and from the wall to the gas, while radiation is the predominant mode for the heat transfer from the wall to the particles. Conduction from the walls to the particles is neglected for the following two reasons: First, the time of collision of the particles with the wall is very small for appreciable amounts of energy to be conducted to the particles. Second, the volumetric concentrations of particles are less than 1%; therefore at any moment there are very few particles in the immediate vicinity of the wall, where any thermal interactions by conduction have to take place. For simplicity the gaseous phase is considered transparent and the particles completely opaque. However, the model can be easily modified to take into account the effects of a Gray gas or partially reflecting particles.

The velocities of the two-phase mixture are low enough, so that critical conditions are never met in the flow domain. Therefore, there is no reason to expect thermodynamic non-equilibrium between the gaseous phase and the particles. This is equivalent to saying that frozen flow is not expected in the applications considered for this study. In addition, the density ratio of the condensed to the gaseous phase is large enough for the Kelvin–Helmholtz effect [18] to be negligible. Hence, the temperature of the particles is a function of the partial pressure of its vapor in the gaseous phase (but is not equal to the vapor temperature). When the composition of the flowing mixture is homogeneous then the particle temperature is given as a function of the total pressure. Changes of the pressure result in particle temperature changes according to the Clausius–Clapeyron relation. The rate of change of temperature in terms of the partial pressure may be written as follows:

$$\frac{dT_p}{dt} = \frac{Tv_{fg}}{h_{fg}}\left(\frac{dP}{dt}\right), \qquad (5)$$

where h_{fg} is the latent heat of the substance, v_{fg} is the volume change related to the phase change and T is the absolute temperature.

Heat transfer to the particles occurs via the convection mode from the gas and the radiation mode from the walls. Thus, the heat flux absorbed by the particles is written as follows:

$$\dot{Q}_p = 4\pi\alpha^2 Nh_p(T_g - T_p) + 4\pi\alpha^2\sigma N(T_w^4 - T_p^4), \qquad (6)$$

where σ is the Stefan–Boltzmann constant, and h_p is the convective heat transfer coefficient for the particles, which must be supplied by an empirical relation. A semiempirical expression recommended in ref. [13] is adopted here for this purpose. Because low particle concentrations are assumed, the effect of particle shadowing in the radiation term is negligible. Regarding the radiation term it may be proved by dimensional analysis (and was also observed in the calculations) that unless T_w is greater than 1500 K, the convection part dominates the two modes of heat transfer in the case of small particle (less than 1 mm diameter) flows.

The heat flux absorbed by the particles manifests itself in two ways: it causes the evaporation of some of the mass of the particles and contributes to the change of its temperature. Thus, one may write the following expression for the rate of mass per unit volume undergoing phase change:

$$\dot{m}_s = \frac{\dot{Q}_p - N m_p c_p \left(\dfrac{dT_p}{dt}\right)}{h_{fg}} \quad (7)$$

where h_{fg} is the latent heat of the substance (for sublimation or vaporization) and c_p is the specific heat of the particles or droplets. Given that the rate of temperature change of the particles is controlled by the pressure change, according to equation (8), the last two equations yield the rate of mass exchange (per unit volume) between the condensed and the vapor phase. The latter is related to the rate of change of the radius of the particles by a mass balance equation

$$\dot{m}_s = -\frac{d}{dt}(N m_p) = -4\pi\alpha^2 N \rho_p \frac{d\alpha}{dt}. \quad (8)$$

Heat flux is also transferred to the gaseous phase from the wall at a rate, which is given by the usual convection relations in terms of a convection coefficient h_w. This coefficient is given by an empirical relationship [5, 14, 15] which takes into account the presence of particles in the flow.

With the heat fluxes to the particles given by equation (8) and the convection to the gas known, the energy equation for the gaseous phase may be reduced to an expression for the temperature change of the gas as follows:

$$\rho_g c_{pg}\left(\frac{dT_g}{dt}\right) = \frac{4h_w}{D}(T_w - T_g) + 4\pi\alpha^2 N h_p (T_p - T_g) \quad (9)$$

where c_{pg} is the specific heat of the gas at constant pressure. In the above equations the particles are assumed to absorb the radiation completely. This assumption is made for the simplicity of the calculations which are focused on the phase changes rather than radiation characteristics of the mixture. The effects of finite reflectivity can be easily incorporated in the heat flux equations by including the appropriate reflectivity and absorbtivity coefficients.

The turbulence model

The Reynolds decomposition of gas velocities was used for the two-dimensional flow field considered

$$U_g = \bar{U}_g + u'_g \quad (10a)$$

and

$$v_g = \bar{V}_g + v'_g \quad (10b)$$

where the denotes time average quantities and ′ the time fluctuations. The flow domain is a cylindrical pipe and for this reason the usual pipe-flow assumptions are made, namely that the time average longitudinal velocity profile obeys the $1/n$ velocity profile with $n = 7$ [19, 20] and that the radial time-average velocity is zero. The fluctuating components u' and v' follow a Gaussian probability density distribution function with standard deviation equal to the turbulent intensity of the flow. Since turbulence in a pipe flow is anisotropic the intensities in the radial and longitudinal directions are different. Furthermore, the turbulence fluctuations are correlated with a correlation coefficient R which is a function of position in the pipe [20]. Thus, the turbulence model may be written as follows:

$$u'_g = R_1 \sigma_u \bar{U}_{gc} \quad (11a)$$

and

$$v'_g = \sigma_v \bar{U}_{gc}[R R_1 + R_2(1 - R^2)^{1/2}] \quad (11b)$$

where R_1 and R_2 are Gaussian random numbers, R is their correlation coefficient, $\bar{U}_{gc}$ is the centerline gas velocity and σ_u and σ_v are the turbulence intensities. The last three variables are position functions and are obtained from a compilation of experimental data [20].

The interaction time between the particles and a turbulent eddy is the minimum of three time scales:

(a) the characteristic time of the particle

$$\tau_p = 4\alpha^2 \rho_p / 18\mu \quad (12a)$$

(b) the residence time of the particle in an eddy

$$\tau_r = l_e / |U_{rel}| \quad (12b)$$

and

(c) the eddy life-time

$$\tau_e = l_e / (2k/3)^{1/2} \quad (12c)$$

where k is the kinetic energy of the turbulent eddy, l_e its length scale [20, 21] and U_{rel} is the relative velocity of the particle with respect to the eddy. It was observed in the calculations that in horizontal flows the eddy life-time was usually the interaction time of the particle with the eddy, except for the cases when the particles became close to complete sublimation. In the latter case the radius of the particle is extremely small and the characteristic time of the particle is the minimum of the three time scales. For vertical flows it is the residence time of the particle which dominates except again for the cases when particles are close to complete sublimation.

The above set of equations (1)–(12) constitute a system of differential and algebraic equations, which describes the phase change of the gas-particle system. This system of equations may be solved by a time marching method to yield the time evolution of the system. Since random numbers are being used for the simulation of turbulence a Monte Carlo approach has been used to obtain ensemble-average quantities of interest. It must be pointed out that a dimensionless representation of the conservation equations is given in ref. [15] and more details for the choice of the closure equations may be found in refs. [15, 17, 20].

PARTICULATE FLOW PAST A WALL TEMPERATURE STEP

As an application of the subject of heat transfer in particulate flows with phase change we consider the case when the two-phase mixture passes through a section where the wall temperature of the duct undergoes a temperature step from T_{w0} to T_w. For simplicity it is assumed that this happens at $t = 0$ and that the solids and gas have equal velocities and temperatures. Because the effects of radiations are taken into account there is no restriction on the magnitude of the temperature step imposed.

When the suspension enters the domain of higher temperature T_w the gas is heated up and accelerates, thus causing the acceleration of the particles. At the same time heat is transferred to the particles causing some of them to sublimate. The phase change is a source of mass for the gaseous phase resulting in further acceleration of the gas and, through the drag mechanism, of the whole mixture. The process of phase change and acceleration stops when all the condensed phase has evaporated and the resulting vapor is heated up to the wall temperature. It must be pointed out that the continuous acceleration of the gas causes a finite relative velocity between the gas phase and the particles, which always lag behind the gas. Thus, the Reynolds number of the particles (measured in terms of relative velocity) becomes finite, a phenomenon which results in higher particle acceleration and convective heat flux from the gas to the particles. This in turn accelerates the phase change process.

Part of the relative velocity is due to the acceleration of the vapor phase and another part to the presence of velocity fluctuations which are modelled as eddies. The instantaneous velocity of the eddy includes the random components u' and v'. Particle(s) entering an eddy experience the effect of these fluctuations in addition to the time-average relative velocity. Hence, their instantaneous relative velocity is higher and because of this their convective heat and mass transport coefficients are enhanced.

CALCULATIONS AND RESULTS

Numerical calculations were made for the temperature step case based on the phase-change model described above. The working equations were solved by an explicit time-marching scheme. For accuracy and for computational stability the time step in the calculations was taken as the interaction time of the particles with an eddy as defined in equations (12a)–(12c) (actually, for higher computational accuracy $0.2\tau_p$ was taken as the characteristic time for the particles instead of τ_p). The evaporating droplets have the properties of water substance in all calculations. The Gaussian random numbers for the simulation of the turbulence quantities were obtained from a standard computer subroutine. Some of the results of the computations are shown in the figures that follow.

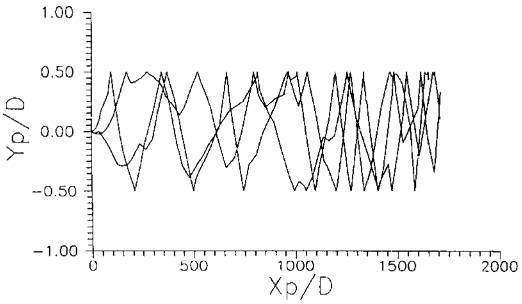

FIG. 1. Three trajectories of droplets released at the center of the pipe.

Figure 1 shows the trajectories of three water droplets released at time $t = 0$ at the center of a horizontal pipe. The initial diameter of the droplets was 0.5 mm and the wall temperature step from 120 to 700°C; the initial pressure was 2 bar and the flow Reynolds number based on the initial conditions 51 500. For the computations it was assumed that droplets collided elastically and instantaneously with the wall. Thus, no droplet deposition was allowed in the model. The effect of random fluctuations of the vapor velocity is evident in the three trajectories. Several collisions with the walls are also obvious.

Figure 2 shows the instantaneous radii of two evaporating droplets initially of 0.5 mm radius experiencing a wall temperature step from 120 to 700°C and with an initial Reynolds number for the flow equal to 51 500. The difference in the instantaneous sizes is caused by different rates of evaporation. This is due to the fact that because of turbulence the two droplets experience different vapor velocity fields and their transport properties differ accordingly. However, it is obvious from the final results that despite the fact that the droplets are subjected to two different random fields the difference in two times of complete evaporation is only 2%.

Of importance to engineering calculations is the pipe length and the total time it takes for the droplets to evaporate as well as the temperature of the vapor at the instant the droplets evaporate as a function of wall temperature. For the computation of these quantities it is necessary to average the corresponding

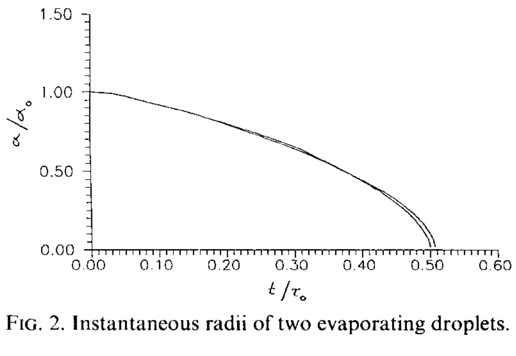

FIG. 2. Instantaneous radii of two evaporating droplets.

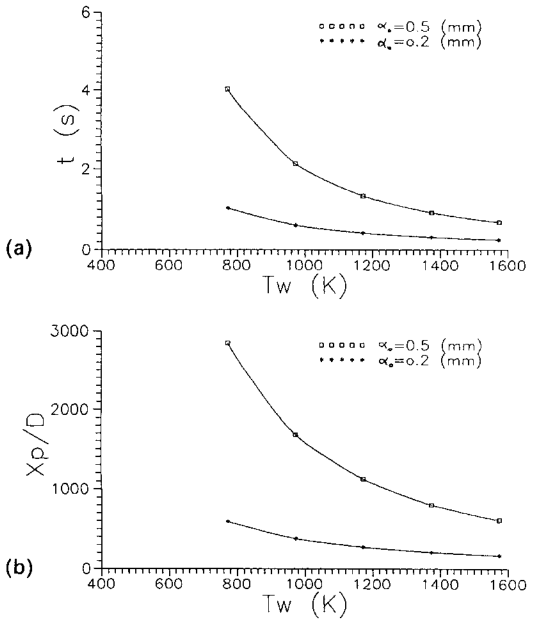

FIG. 3. (a) Effect of the wall temperature on the time required for complete evaporation. (b) Effect of the wall temperature on the evaporation length.

quantities of an ensemble of particles subject to the turbulent flow field as described by equations (10)–(12). A sensitivity analysis of the computation results showed that the average quantities of interest converged to within 0.5% when more than 700 particles were used in the ensemble. In the calculations that follow 990 particles were released from different initial radial positions and the results obtained were averaged to obtain the ensemble averages.

Figures 3(a) and (b) show the influence of the wall temperature on the evaporation length and time. The results are for water droplets of initial sizes equal to 0.5 and 0.2 mm and initial temperatures of 120°C (393 K). As expected the higher wall temperature results in a shorter evaporation time and shorter evaporation lengths. It is also of importance that smaller droplets evaporate much faster than the bigger ones. This is due to the much higher initial amount of mass the bigger droplets have.

The time evolution of the gas temperature during the droplet evaporation process is shown in Fig. 4 for three different wall temperatures of 500, 700 and 1100°C. It is assumed that initially the gas is at the same temperature as the droplets (120°C). The three curves show a fast increase in the gas temperatures initially, followed by a very slow rate of increase. The rapid temperature increase is due to the fact that a great deal of heat is absorbed from the wall by the gas and not much from the gas by the droplets (because initially gas and droplets are at the same temperature and heat transfer between the two phases is low). When the gas reaches an intermediate temperature between T_{g0} and T_w, the convection of heat from the gas to the particles becomes dominant in the heat balance and most of the heat flux from the wall to the two-phase mixture is finally absorbed by the evaporating droplets (it may be said that the presence of droplets keeps the gas cooler). Therefore, the temperature of the vapor phase rises very slowly as may be seen in the figure. When the droplets become very small (and hence the convective heat transfer to them becomes very low) the rate of increase of the gas temperature is faster. When the droplets evaporate completely all the heat is absorbed by the gas. Then the gas temperature is expected to increase rapidly and to finally approach asymptotically the wall temperature (the usual single-phase relaxation solution to the gas temperature will apply).

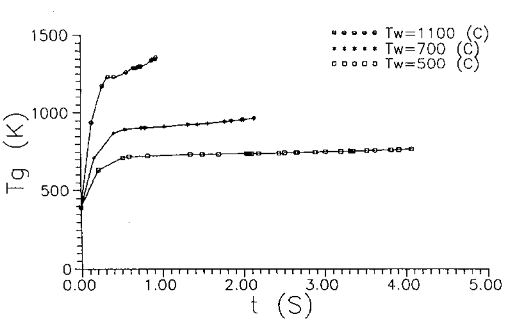

FIG. 4. Vapor temperature as a function of time for three different wall temperatures.

The effect of the turbulence level intensity on the time and length of evaporation was examined. It is known that turbulence intensity may be artificially modulated by the placement of certain components in the boundary layers. For this reason parametric calculations were conducted on the turbulence intensities. Thus, σ_u, σ_v and u^* (the friction velocity) were multiplied simultaneously by a factor λ ranging between 0 and 2. The case for $\lambda = 0$ represents complete suppression of turbulence, the case $\lambda = 1$ represents normal turbulence levels with the closure equations for the turbulence intensities obtained from ref. [20] and the case $\lambda = 2$ assumes a turbulence level twice as much as the normal. The results for the time of evaporation and for the length of pipe required for evaporation are shown in Figs. 5(a) and (b), respectively. The two curves represent two initial Reynolds numbers (51 500 and 17 200). It is apparent that the level of turbulence intensity plays an important role in the evaporation time and pipe length; a reduction of up to 20% on both is achieved by doubling the level of normal turbulence.

One parameter, which influences the results of the evaporation considerably is the initial radius of the particles or droplets α_0. Its influence lies in the fact that the heat flux to the particles is proportional to the square of the radius, while the concentration by volume or mass is proportional to the cube of the radius. The effect of the initial radius (α_0) on the time required for complete evaporation is shown in Fig. 6. T_w is 900°C for the two curves which represent Reynolds numbers of 51 500 and 17 200. It is observed that the originally smaller droplets, which have larger

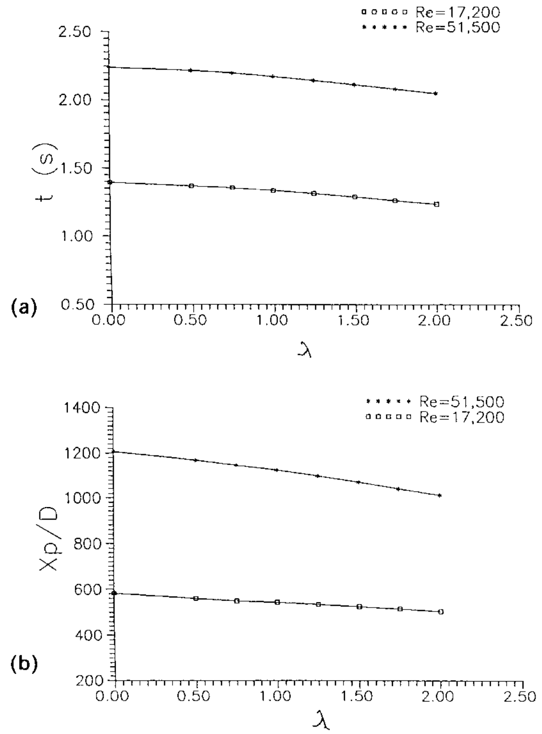

FIG. 5. (a) Effect of turbulence modulation on the time required for complete evaporation for two Reynolds numbers. (b) Effect of turbulence modulation on the pipe length required for complete evaporation for two Reynolds numbers.

total surface area, evaporate in a small fraction of the total time required by those with bigger original sizes.

Since the emphasis of the present work is on the effect of turbulence on evaporation and sublimation, computations on other parameters were not made. The qualitative influence of several other parameters on phase change may be found in ref. [15] where more parametric calculations and results with substances other than water are reported.

CONCLUSIONS

This study shows the development of a mathematical model for the turbulent motion of particles or droplets in a duct, while they undergo a phase change. The model treats the two phases separately and allows for thermal and mechanical non-equilibrium. The conservation and closure equations for the properties of the flowing mixture of gas and particles are obtained. The turbulence closure equations were obtained from standard experimental data available in the boundary layer literature. A Monte Carlo simulation of the trajectories of 990 particles in the flow was used for obtaining the quantities of interest. Thus, the instantaneous velocity field is obtained by the use of two Gaussian random numbers correlated according to experimental data in order to simulate the relationship between u' and v'. The differential equations, which describe the phase change process, are solved for each one of these particles and the final results are averaged.

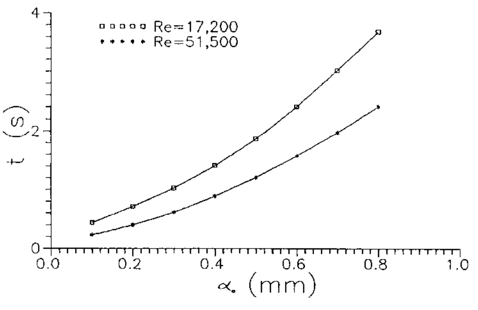

FIG. 6. The effect of the initial droplet radius on the time required for complete evaporation.

The solution of the system of differential equations was accomplished for a substance having the thermodynamic and transport properties of water. The results showed that the rate of phase change increases with higher wall temperature or lower particle diameter. The temperature of the gaseous phase remains almost constant, during the time when phase change occurs and increases rapidly when the phase change is completed. Therefore, during most of the phase change process the temperatures of both phases remain almost constant (although the two are different). It was found that turbulence plays an important role in the phase change process and that the evaporation time is reduced by 20% when the turbulence level is doubled with respect to the normal. Therefore, it may be concluded that, other things being equal, turbulence enhancement elements may be advantageously used for the improvement of phase change processes.

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EFFET DE TURBULENCE SUR LE CHANGEMENT DE PHASE DES GOUTTES OU DES PARTICULES DANS LES CONDITIONS DE NON-EQUILIBRE

Résumé—On développe un modèle qui décrit le changement de phase (par sublimation ou par évaporation) d'une goutte liquide ou d'une particule solide dans un écoulement gazeux turbulent. Pour ce faire, on donne les équations de conservation et de clôture appropriées. La turbulence est représentée par une distribution aléatoire convenablement corrélée. Le système d'équations est résolu numériquement dans le cas où le mélange de deux phases est soumis à une augmentation subite de la température de la paroi. La méthode de Monte Carlo est appliquée pour obtenir les valeurs moyennes de grandeurs qui caractérisent le champ d'écoulement. On étudie l'influence de certains paramètres (taille initiale des particules, intensité de la turbulence, importance du saut de la température de la paroi) sur le taux d'évaporation ou de sublimation de la phase condensée. La température du gaz, sa vitesse, la distance parcourue et le temps, nécessaires au changement total de phase, sont calculés.

EINFLUSS DER TURBULENZ AUF DEN PHASENWECHSEL AN TROPFEN UND PARTIKELN UNTER NICHT-GLEICHGEWICHTSBEDINGUNGEN

Zusammenfassung—Zur Beschreibung des Phasenwechselvorganges (Sublimation oder Verdampfung an Tropfen und Partikeln in einem turbulent strömenden Gas wird ein Modell entwickelt. Zu diesem Zweck werden die zugehörigen Erhaltungs- und Schließungs-Gleichungen hergeleitet. Die Turbulenz wird durch eine geeignete Korrelation von Gauss'schen Zufallszahlen simuliert. Für den Fall, daß das Zweiphasengemisch einer sprunghaften Änderung der Wandtemperatur ausgesetzt ist, wird das Gleichungssystem numerisch gelöst. Die gemittelten interessierenden Größen des Strömungsfeldes werden unter Verwendung des Monte-Carlo Verfahrens ermittelt. Der Einfluß unterschiedlicher Parameter (wie z. B. anfängliche Partikelgröße, Turbulenzintensität und Stärke der sprunghaften Wandtemperaturänderung) auf die Geschwindigkeit des Phasenwechsels der kondensierten Phase wird untersucht. Die Gastemperaturen, Geschwindigkeiten, Abstände und Zeiten für einen vollständigen Phasenwechsel werden berechnet und dargestellt.

ВЛИЯНИЕ ТУРБУЛЕНТНОСТИ НА ФАЗОВЫЙ ПЕРЕХОД КАПЕЛЬ И ЧАСТИЦ ПРИ НЕРАВНОВЕСНЫХ УСЛОВИЯХ

Аннотация—Разработана модель для описания процесса фазового перехода (сублимации или испарения) капель и частиц в газообразной среде в условиях турбулентного течения. Получены уравнения сохранения и замыкания для исследуемого процесса. Турбулентность моделируется соответствующим гауссовским распределением случайных чисел. Численно решается система уравнений для случая, когда двухфазная смесь нагревается за счет скачкообразного увеличения температуры стенки. Методом Монте-Карло определяются средние величины поля течения. Устанавливается влиение нескольких параметров (таких как начальные размеры частиц, интенсивность турбулентности и величина скачка температуры стенки) на скорость превращения конденсированной фазы. Приводятся результаты расчетов температур, скоростей, а также расстояний и промежутков времени, необходимых для осуществления фазового перехода.