EFFICIENCY EVALUATION OF A CONDENSATIONAL SCRUBBER FOR PARTICULATE ABATEMENT: PRELIMINARY RESULTS

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Abstract
A theoretical and experimental preliminary evaluation of the effectiveness of the condensational growth technique for particle abatement is presented. On the ground of studies present in literature, the heterogeneous nucleation rate and particles activation probability have been estimated as function of environmental conditions and particle dimensions.
In addition, the vapor nucleation on graphite nanoparticles has been experimentally followed in a laminar flow chamber. Intensity of laser light scattered from the control volume has been collected along the chamber axis and correlated with the variation of particle dimension. The effect of vapor concentration on abatement efficiency has been evaluated for fixed feed conditions. It was shown that an increase in vapor concentration positively affects nucleation rate and the temperature at which it becomes effective.

Introduction
One of the main concerns in pollutant reduction and abatement is related to the difficulties in eliminating combustion derived particles in a certain range of dimension in post treatment devices. For particle diameter ranging from 0.1μm to 1μm, the removal efficiency of traditional abatement systems, based on diffusion, inertial impact as well as sedimentation, decreases to about 20%, thus making the application of such techniques useless [1]. To make them operate in correspondence of optimal working conditions, an increase of dimension of particles to be eliminated can be considered upstream to standard cleaning processes. A promising technique for industrial applications relies on increasing the diameter of fine and ultra-fine particles by means of condensation of water vapor on the particles themselves, especially when stream to be treated contains a significant amount of vapor. This is the case of flue gases coming from MILD or coal Oxy-Fuel Combustion processes, where water vapor could be used as diluent in order to reduce the maximum temperature.
The capture of particles dispersed in the flue gases by means of condensational particle growth is a complex process, resulting from single sub-processes that

evolve in series and/or parallel. Thus, vapor nucleation on particles, droplet growth and coagulation depend both on environmental parameters and particle characteristics. Temperature, pressure, vapor concentration, fluid-dynamic field as well as particle composition, dimension and morphology influence each single sub-process thus making difficult to directly relate an overall trend to a specific effect. Such severity is increased by the continuous change of local environmental conditions caused by vapor condensation itself. Beside, plenty of studies are present in literature on homogeneous and heterogeneous condensation that point out empirical, semi-empirical and theoretical expressions of nucleation rate that are often very sensitive to the condition to which they have been obtained [2]. In this framework, the present study aims to show an evaluation of the effectiveness of the condensational growth of particle for their abatement with a twofold approach. From the exploitation of literature, indication on dependence of heterogeneous nucleation rate and activation probability on temperature, vapor concentration and particle diameter have been pointed out. Then, the process has been followed from experimental point of view and the results compared with theoretical evaluations.

General aspects

Heterogeneous nucleation rate strongly depends on nucleus properties present in the system, such as their nature, morphology and dimension. The heterogeneous nucleation rate J* is given by [3]:

$$J^* = 4\pi R_p^2 10^{25} \exp\left(-\frac{16\pi}{3} \left(\frac{\sigma_{lv}}{k_B T} \right)^3 \left(\frac{m_l}{\rho_l \ln(S)} \right)^2 \cdot f(\theta, x) \right) \quad (1)$$

In this expression R_p is particle radius, m_l, ρ_1 and ν_l are the molecular weight, the density and specific volume of the liquid phase, σ_{lv} is surface tension of liquid-vapor interface, S is saturation ratio, k_B is Boltzmann constant and T is the absolute temperature. The term f(θ,x) quantitatively describes the reduction of the nucleation barrier due to the presence of foreign bodies, for an insoluble spherical particle of radius R_p, it depends upon, contact angle θ, and the relative size between the particle and the critical embryo size R_k of condensed vapor phase, $x=R_p/R_k$ [4].
The activation probability $P_d(\tau)$ of a particles with respect to the nucleation process is defined as the ratio of the concentration of activated particles to their initial concentration [3]:

$$P_d(\tau) = 1 - e^{-J^*\tau} \quad (2)$$

Particles are considered to be activated once their activation probability is higher than 0.5. τ is, approximately, the time associated with heterogeneous nucleation of the supersaturated vapor. Its value varies from less than 0.001 s up to 1000 s in the literature [3].
In Figure 1 the heterogeneous nucleation rate computed from the equations (1) for a carbonaceous particle with a contact angle θ=85° and a characteristic dimension

$D_p=2R_p$ of about 100 nm, in correspondence of vapor volumetric percentages (X_v) of 0.1, 0.25, and 0.35 and a temperature T varying from 275 to 373 K. On the same diagram supersaturation profiles for the same conditions have been reported.

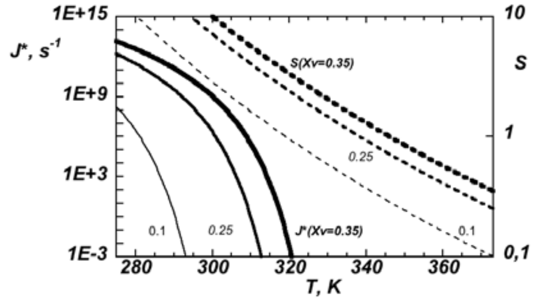


Figure 1. J* (solid), and S (dashed) profiles versus T for different X_v.

Experimental solutions and configuration

A 10 cm square cross section laminar flow chamber has been used for the experimental tests. A carrier gas, steam and/or particles from spark generator (PALAS GFG1000) are axially fed to the chamber with a 2 cm injection tube. An inert gas flow is fed externally to the mainstream to prevent the diffusion of the droplets and particles toward the chamber walls. The steam is fed by means of an evaporator able to provide a controlled steam flow. A heater system, controlled remotely, avoids the steam condensation along the feed line. A Thermocouple placed in proximity of the outflow section of the main flow allows to monitor and control the temperature of the working fluid.

The process has been followed along the chamber axis (z) by means of elastic light laser scattering. The second harmonic (532 nm) of a Nd-YAG laser has been used as excitation wavelength. The elastically scattered light is focused on a APD type photodiode. The dimension both of laser beam and of detector, along with the magnification ratio of the collection system used result in a control volume 0.5mm tall and 3mm deep. Polarization rotators and analyzers are placed on optical path of the system to allow the measurements of the vertical (I_{VV}) and horizontal (I_{HH}) components of the scattered light. The collected signal, along with the intensity of incident laser beam for each pulse, are recorded by an oscilloscope. Each experimental data are obtained by the average of 2000 runs.

Results and Discussion

The axial profiles of the elastic light scattered intensity have been obtained for four vapor inlet concentration X_v, that are 0%, 10%, 25% and 35%. Thus, X_v= 0% corresponds to the case where only particles and carrier are fed to the chamber. By increasing the vapor concentration from 0% to 35%, the percentage of the carrier has been changed in such way that the fluid-dynamic conditions are equivalent in all the condition considered.

In Figure 2(a) the polarization ratios ($\gamma = I_{HH} / I_{VV}$) obtained at T=375K for the X_v considered are shown.

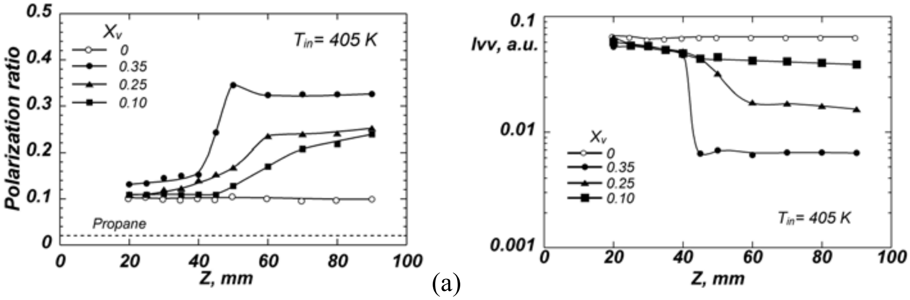


Figure 2. (a) γ and (b) I_{vv} as function of axial coordinate.

On the same diagram the polarization ratio of propane, obtained with the same experimental set up, is reported with a dashed line as reference value to show the limit of the detection system.

For X_v=0% γ value is almost constant around the value of 0.1 along the chamber axis, in congruence with the size of the particles fed. It is well known from literature [5], that in the case of particle light scattering described by the Rayleigh model, even though polarization ratio collected at 90° should be equal to zero, its experimental value ranges between 0.01 and 0.1 due to the finite collecting angle of diagnostic system. These γ values are consistent with the one calculated taking into account the characteristics of the collection system and the size distribution and characteristics of generated particles. This is shown in Fig. 3 where γ computed for carbonaceous particle (dashed line) and water droplet (solid line) are reported as function of particle and droplet diameter. The invariance of γ with z at X_v=0% corresponds to the invariance of I_{vv} collected in the same conditions and reported in Figure 2(b).

The analysis of the polarization ratio measured in presence of vapor is of particular interest. Figure 2 (a) shows that for X_v=35%, from z=20 mm to z=40, γ is constant at a value slightly higher than that measured for X_v=0%. This trend suggests that up to 40 mm there is no significant change in the scattereres dimension. This means that heterogeneous nucleation on particles present in the stream is not fully activated. In addition, the liquid clusters or layer that forms on the particles are not large enough to sensibly modify the optical properties of the particles.

For z higher than 40 mm, the polarization ratio sharply increases and reaches a value of about γ =0.35 at z=44mm. This trend indicates that the nucleation process has been suddenly activated and the surface growth and coalescence lead to the formation of larger droplets. The related I_{vv} profile, reported in Fig.2(b), shows a complementary trend. It is very close to the values collected for Xv=0% and slightly decreases from 0.6 to 0.5 a.u. passing from 20mm to 40mm. For z higher than 40mm, it sharply decreases to about 0.06 a.u, sticking to this value up to z=90mm. The decrease of scattered light intensity despite the increase of scatterers diameter has to be related to a decrease of number of scatterers present in the control volume, assuming that $Ivv: ND^6$ (N= number of scatterers in the control

volume, D scatterers diameter). Such behavior can be related to the inclusion of carbonaceous particles in water droplets, which, in turn, grow and coalesce.
If a pure water droplet is considered, the plateau value of polarization ratio of about 0.7 measured at X_v=35% would correspond to a scatterer diameter of about 400nm, as shown on the computed polarization ratio profile reported in Fig. 3. Therefore, it is possible to suppose that the dimension of scatterers present in the control volume, constituted by water and carbonaceous particles, lies in the gray region reported in the Fig. 3, delimited by the γ curve of soot and the one related to the water.

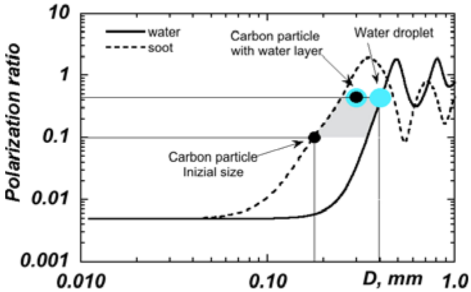
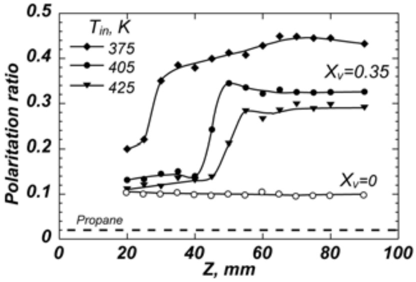
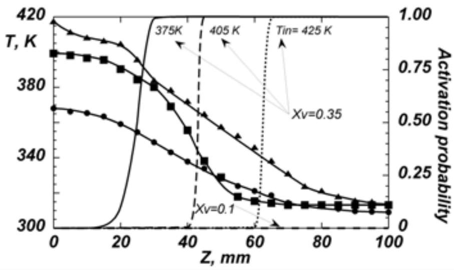


Figure 3. Computed γ as function of particle diameter.

Different behavior is shown by the experimental results obtained for X_v= 25% and 10%. For these cases, the profiles reported in Figure 2(a) show that γ value remains at value of about 0.11, slightly higher than the value of the soot particles up to z=40 mm. For z higher than 40 mm, γ slightly increases and reaches a maximum of 0.25 at z = 90 mm in both cases. In this case it is possible to affirm that heterogeneous nucleation occurs, but the vapor concentration is such that the increase in droplet size is limited with respect to higher vapor concentration.
The effect of inlet temperature Tin on the collection mechanism can be analysed in the Figure 4 (a) where γ measured for a Tin of 375K, 405K and 425K has been reported. As expected, a decrease of T_{in} causes a reduction of induction time and, therefore, an activation of the processes at lower z.
The evolution of the process pointed out by the analysis of γ and I_{vv} is consistent with the indications provided by the evaluation of the activation probability calculated in the experimental conditions considered, according to the temperature profile measured along the axis. Figure 4(b) reports the temperature profiles and the corresponding activation probability computed by considering the particle diameter and properties equal to the one used in the experimental analysis. It is clearly shown that the activation probability reaches its maximum value in all the cases corresponding to an X_v=35%. For T_{in}=375K and 405K the characteristic times of the process are similar to the one obtained by the experimental evaluation of γ. Different consideration applies for T_{in}=425K, where the theoretical characteristic induction time is longer than the one obtained with experimental measurement.



(a)



(b)

Figure 4. (a) γ and (b) T_{in} and P as function of axial coordinate (z).

Conclusion

A preliminary evaluation of the particle abatement by means of condensational growth techniques has been carried out showing that it is possible to capture the dispersed particles in the water droplets with high efficiency in dependence on operative conditions. It has been shown that higher inlet vapor concentration as well as lower working temperature increases the final size of the particles thus improving the removal of droplets from the gas stream. In addition, it has been demonstrated that the activation probability, evaluated according to the equation (2) can give an indication of the effectiveness of the process with respect to the operative condition considered.

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