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# Study of aerosol behaviour in filmwise condensation processes with the presence of inert gas

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ABSTRACT

The appearance of aerosols in condensation processes may result in a loss of condensate mass, a reduction of efficiency, pollution and damage to equipment. The presence of inert gases in condensation is frequent and can lead to the formation of aerosol particles. Equipment used in industrial condensation, gas cleaning, the removal of pollutants or the recovery of valuable substances comprise some examples of interest. The complexity of the physical phenomena occurring simultaneously makes the study of these systems difficult and it is thought that modelling might help to better understand their behaviour. A model has been developed in this study that includes the condensation of the gaseous mixture and phenomena related to the presence of liquid particles. The model solves the conservative equations for species continuity, energy and the number of liquid particles. It also includes the precipitation of liquid particles via thermophoresis, diffusiophoresis and gravitational deposition, homogeneous nucleation and coagulation induced by the Brownian movement of the particles. A condenser presenting a simple shell-and-tube geometry was selected and subjected to a unidimensional spatial discretization. The particle size interval of the aerosol population was discretized following a sectional method of moving intervals. The interaction between continuous and discrete phases was calculated as condensational growth in non-dilute and non-ideal media. Some cases were solved for water liquid particles and vapour mixed with air and a comparison was carried out using experimental data from a previous study from the literature providing a good fit. It was observed that the condensation rate is not radically altered by the presence of particles, although the persistence of remaining growing droplets dispersed in the gas could produce the aforementioned undesirable effects.



## 1. Introduction

Filmwise condensation occurs when vapour condenses on a continuous liquid film formed around a cooled surface. It is the most important mode of condensation in conventional equipment. The presence of non-condensing species mixed with the vapour is usual. This can be a result of undesired gas inlets, or because the species is part of the process. The concentration of the inert species is higher next to the liquid film, which acts as a barrier for vapour condensation. The condensing species must diffuse through the inert species towards the liquid film. At the same time, the heat also diffuses towards the cooled surface. The combination of diffusive heat and mass transfer can lead to metastable states of supersaturation in the gas. Bulk condensation can thus occur and a discrete phase may appear in the form of liquid particles dispersed in the gas mixture. The combination of the continuous and the discrete phases forms a liquid aerosol, also called fog.

Fog formation has recently been observed in experimental processes involved in the recovery of fatty acid fractions by condensation in the presence of nitrogen as the inert gas [1]. This phenomenon was thought to be the cause of some mass imbalances in the condenser. The need thus arose to develop a tool capable of calculating heat and mass transfer in condensers in which an inert gas and a discrete liquid phase are present.

Aerosols may be present in commonplace industrial equipment like burners, nozzles, turbines, heat recovery boilers and condensers [2–5]. The phenomenon has been studied in industrial processes such as absorption, scrubbing and gas cleaning [6–8]. The cleaning of gases containing hazardous or pollutant particles is of interest in the field of nanotechnology, biotechnology and drug administration, among others. Aerosols may also form in containment condensers for the nuclear industry [9–11]. Systems with a phase change including a gaseous mixture of vapour and

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## Nomenclature

| | |
|---|---|
| $A_{CS}$ | cross section surface area |
| $C_c$ | slip correction factor |
| $c_p$ | specific heat capacity at constant $p$ |
| $\bar{c}_p$ | mean thermal velocity of the particle |
| $D$ | diameter |
| $D_B$ | Brownian diffusion coefficient |
| $D_g$ | binary diffusion coefficient |
| $D_p^*$ | critical diameter of the particle |
| $\overline{D}_{pg}$ | median diameter in number concentration |
| $\overline{D}_{pV}$ | mean diameter in volume concentration |
| $f_{i,j,k}$ | coagulation partition coefficient |
| $g$ | gravitational acceleration |
| $G_B$ | geometrical factor for size bin definition |
| $H$ | condensation rate |
| $h$ | specific enthalpy |
| $h_c$ | convective heat transfer coefficient |
| $h_m$ | convective mass transfer coefficient |
| $h_{Nuss}$ | filmwise cond. heat transfer coefficient |
| $J$ | nucleation rate |
| $j$ | mass flux |
| Kn | Knudsen number |
| $k$ | thermal conductivity |
| $k_B$ | Boltzmann constant |
| $L$ | length |
| $m$ | mass |
| $\dot{m}$ | mass flow rate |
| $M$ | molecular mass |
| $N$ | number concentration |
| $\dot{N}$ | change in number concentration with time |
| $N_B$ | number of size bins |
| $n$ | particle size distribution function |
| $n_V$ | particle volume distribution function |
| $\dot{P}$ | particle flow rate |
| Pr | Prandtl number |
| $p$ | pressure |
| $\dot{Q}$ | heat transfer rate |
| $q$ | heat flux |
| $R_U$ | ideal gas universal constant |
| $S$ | saturation ratio |
| $S_h$ | volumetric heat source term |
| $S_m$ | volumetric mass source term |
| $S_{Np}$ | volumetric particle number source term |
| Sc | Schmidt number |
| $T$ | temperature |
| $t$ | time |
| $\vec{u}$ | unitary direction vector |
| $V$ | volume |
| $VP$ | particle volume concentration |
| v | velocity |
| $y$ | gas phase mole fraction |

*Greek symbols*

| | |
|---|---|
| $\beta_{i,j}$ | coagulation kernel |
| $\Delta H_{fg}$ | specific latent heat of condensation |
| $\eta$ | relative rate of deposition |
| $\lambda$ | mean free path |
| $\mu$ | dynamic viscosity |
| $\rho$ | density |
| $\sigma_g$ | geometric standard deviation |
| $\sigma_{lg}$ | liquid–gas surface tension |
| $\xi_{Nuss}$ | correction factor for Nusselt expression |

*Subscripts*

| | |
|---|---|
| 0 | condenser inlet |
| *aer* | aerosol |
| *b* | bulk |
| *cgn* | coagulation |
| *cond* | condensate |
| *dif* | diffusive |
| *dph* | diffusiophoresis |
| *g* | gas mixture |
| *gd* | gravitational deposition |
| $i, j, k$ | bin counter |
| *ii* | slab counter |
| *in* | inert gas |
| *inlet*, *outlet* | slab inlet and outlet |
| *int*, *ext* | tube inner and outer surfaces |
| *L* | liquid in the condensate film |
| *l* | liquid |
| *m* | molecule |
| *ncl* | nucleation |
| *out* | condenser outlet |
| *p* | particle |
| *S* | liquid–gas interphase at the condensate film |
| *ref* | refrigerant |
| *sat* | saturation |
| *t* | tube |
| *tph* | thermophoresis |
| $v$ | vapour |
| $x, r$ | axial and radial directions |

inert gas plus liquid particles can be found in studies on laminar flow condensers for controlled aerosol generation [12,13] and condensation nuclei counters used in atmospheric science [14–16].

The present study describes a unidimensional model developed to simulate the behaviour of aerosols in a double tube parallel flow condenser. The gaseous mixture of condensing vapour and inert gas containing a discrete phase formed by a population of liquid particles with a size distribution circulates around the inner cooled tube. Film condensation occurs on the outer surface of the tube, which is cooled by a cold water stream.

The interaction between the continuous and discrete phases constitutes an essential part of the analysis and has been the subject of a previous study [17]. The cited study describes the calculation scheme for the condensational growth of the droplets by means of a numerical method based on the finite volume method, designed for non-dilute and non-ideal media. Stefan-flow, thermal diffusion and the Duffour effect around the droplet were included in the calculation of the droplet condensational growth.

Besides condensational growth, the study of the aerosol includes homogeneous nucleation of new droplets, coagulation of particles by Brownian motion, and precipitation of particles by thermophoresis, diffusiophoresis and gravitational deposition.

The physical processes involved in fog condensation are described in this paper. The solved equations and the strategies for solving them are also presented, together with a description of the numerical model. The results of a set of solved cases are analysed in order to better understand the behaviour of these complex systems. Experimental data taken from the study by Manthey and Schaber [18] is then used to compare the results of the model with a real case. The main objectives are to obtain information on the relative importance of the different phenomena occurring simultaneously and to determine the influence of the presence of aerosol liquid particles on the process of condensation.