

# ***RAPID EVAPORATION OF A SUPERHEATED R134A JET***

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## **ABSTRACT**

The understanding of accidental releases of flammable and toxic pressure-liquefied gases holds an interest in the safety field. In case of such an accident, a flashing vapor explosion takes place resulting in a very dense two-phase cloud. For understanding the source processes of flashing for risk assessment, data related to cloud characteristics such as droplet size, velocity and temperature is needed especially in the near region of the release. The main objective of the present work is to assess the temperature evolution of the two-phase flashing R134A jet originated from a diaphragm type orifice. In the present case, a global temperature measurement is done with intrusive techniques like thermocouples. The temperature measurements show that the flow is stationary at the point wise measurements and is repeatable. The effect of the thermocouple type on the final temperature value is investigated. The effect of the thermocouple type on the final temperature value is also discussed. The temperature results are compared with a simple analytical evaporation model. Sensibility of the model is discussed and documented.

## **1. INTRODUCTION**

Liquid flashing phenomena holds an interest in many areas of science and engineering. As examples one can mention: a) the accidental release of flammable and toxic pressure-liquefied gases in chemical and nuclear industry; the failure of a vessel or pipe in the form of a small hole results in the formation of a two-phase jet containing a mixture of liquid droplets and vapor, b) fuel atomization for improvement of fuel injector technology, c) flashing mechanism occurrence in expansion devices of refrigerator cycles etc.

Violent boiling and aerodynamic fragmentation control the two-phase behavior of flashing flows. The initial, flashing stage of the jet, where the system is furthest from equilibrium is least understood. To investigate theoretically these source processes, knowledge of accurate and reliable data such as distribution of droplet size, velocity and temperature is mandatory. These models are needed in design and safety assessment. The present work focuses on the thermal evolution of an atomized jet when the pressurized liquefied R134-A undergoes a sudden release.

### **1.1 Description of flashing phenomena**

The flashing phenomenon occurs when a liquid is out of thermodynamic equilibrium (see [1], [2], [3], [4], [5], [6] for detailed review). Different story lines may lead to this non-equilibrium state. In the first one, a liquid in equilibrium is heated to a higher temperature while its pressure is maintained constant. In the second case, the liquid is depressurized rapidly keeping its initial temperature constant, so that, because of thermal inertia, the internal temperature finds itself above the saturation temperature at the new pressure condition. The present study focuses on this second scenario.

Under carefully controlled conditions (a pure substance in a perfectly clean and smooth vessel, without any physical disturbance and following a slow and almost reversible process), it is possible for a liquid to be maintained in a meta-stable state without flashing occurrence. However, under most practical circumstances, all the ideal conditions cannot be kept and the meta-stable liquid will return violently to a new equilibrium state thanks to a massive evaporation (i.e. consuming its superheat as latent heat). As stated by Owen and Jalil [6], if the superheat within the depressurized liquid can be conducted to the interface, the latent heat will be released through surface evaporation. If, however, the heat cannot be conducted at a sufficiently high rate, evaporation will occur within the liquid through bubble growth. This process can be extremely sudden and explosive. The bubble explosion serves together with the aero dynamical breakup as a mechanism to offer a maximum surface exchange for the evaporation.

## 1.2 Layout of the paper

The main objective of the present work is to assess the temperature evolution of the two-phase flashing R134-A jet, using intrusive and non-intrusive techniques and compare it to a macroscopic modeling approach. Section 2 will give elements of derivation concerning the model used for the rapid evaporation of a droplet of R134-A after the jet break-up. Section 3 will give description of the experimental set-up and measurement campaigns. Section 4 describes the experimental results and their comparisons with the analytical model.

## 2. PHYSICAL MODEL

A first version of the present model was already presented by Yıldız et al.[7] at ICLASS 2003 without sensibility analysis. Furthermore, the necessity to adopt some correction factor was left unanswered. The following presentation aims to clarify these points without doing a full review of models used for evaporation, reader interested in model derivation will consult Bird et al.[8] or Sirignano [9].

In our approach a relatively simple (1D) formulation is used to predict the temperature evolution of a representative mean diameter of the droplet distribution. Hereafter, the temperature variation inside of the droplet together with the temperature evolution around the droplet will not be taken into account. The droplet and the surrounding gas are both characterized by a single temperature, respectively  $T_d$  and  $T_g$ . Following the derivation of Pretrel [10], the set of first order differential equations may be presented in a reduced form as:

$$\frac{d}{dt} \begin{bmatrix} u_d \\ T_d \\ \Phi_d \\ x_d \end{bmatrix} = \begin{bmatrix} \frac{u_g - u_d}{\tau} \\ \frac{T_g - T_d}{\tau_t} - \frac{L_{hd}}{C_{pd}} \frac{1}{\tau_m} \\ -\frac{\Phi_d}{3\tau_m} \\ u_d \end{bmatrix} \quad (1)$$

The left hand side of Eq. 1 is formed by the time derivatives of the four main variables associated with the droplet. The right hand side contains the driving terms for momentum, energy and mass balances together with the kinetic of the droplet. The reduced form of the driving terms associate a relaxation time for each mechanism of transfer (i.e.  $\tau$ ,  $\tau_t$ ,  $\tau_m$ , are respectively the relaxation time associated with dynamical, thermal and mass transfer for the droplet). Two relaxation times, one for the convection ( $\tau$ ) and one for the evaporation ( $\tau_m$ ), control the droplet equation of energy. The definitions of the relaxation times are given in Equation 2.

$$\begin{aligned} \tau &= \frac{4}{3} \frac{\rho_d}{\mu_g} \frac{\Phi_d^2}{C_D \text{Re}_d}; \\ \tau_t &= \frac{1}{6} \rho_d \frac{C_{pd}}{k_g} \frac{\Phi_d^2}{Nu_d}; \\ \tau_m &= \frac{1}{6} \frac{\rho_d}{\rho_g} \frac{1}{D_{d \rightarrow g} (y_{d,g} - y_{d,g^\infty})} \frac{\Phi_d^2}{Sh_d} \end{aligned} \quad (2)$$

Following Abramzon and Sirignano [11] the definition of the mass fraction ( $y_{d,g}$ ) is given in Equation 3. Here, it is interesting to comment this formulation whenever flashing is concerned. During the experiment, a saturated liquid (R134-A) at ambient temperature and in a thermo dynamical equilibrium is released at atmospheric pressure. Due to the thermal inertia, the liquid “finds itself” with the initial temperature at atmospheric pressure. This temporary state is called a metastable equilibrium. In this configuration and without a proper limitation, the use of a pure equilibrium law such as the one giving the saturation pressure versus the temperature would lead to inconsistencies i.e. a mass fraction exceeding the unity (the saturation pressure at ambient temperature is more than five times higher than the atmospheric pressure). Therefore the mass fraction of Equation 3 is limited by an arbitrary value of 0,99 that cannot be exceeded. When the liquid is out of its thermodynamic equilibrium, this limitation prevents the saturation pressure to be higher than the ambient pressure. A limit on the mass fraction of 0,99 corresponds to a limit of the saturation pressure of about 97% of the atmospheric pressure. An alternative approach would be the implementation of a non-equilibrium saturation pressure.

$$y_{d,g} = \frac{M_{R134A} P_{sat}(T_d)}{M_{R134A} P_{sat}(T_d) + M_{AIR} P_g} \quad \text{with } P_g = (P_{Atm} - P_{sat}(T_d)) \quad (3)$$

In the set of equations defining the relaxation time (Eq.2), four dimensionless numbers appear (i.e.  $Re_d$  for the droplet Reynolds number,  $C_D$  for the droplet drag coefficient,  $Nu_d$  for the droplet Nusselt number and  $Sh_d$  for the droplet Sherwood number). The three last dimensionless numbers involve in their definition the first one i.e; the droplet Reynolds number defined in Eq. 4. The drag coefficient correlation used hereafter is also valid out of the Stokes regime (i.e. when  $Re_d > 1$ ). The Nusselt and Sherwood correlations are the ones used by Abramzon and Sirignano [11] written in a form valid out of the Stokes regime. Inside of the Stokes regime,  $Re_p^{0.077}$  is replaced by “1” in these two last correlations. Following the advice of Bussmann and Renksizbulut [12], the correction factor, which is generally used in combustion of solid particles, and known as the “Renksizbulut-Yuen correlation”, is not applied here (in this last reference the use of this correction is not advised in the case of a highly evaporative particle).  $Pr_d$  and  $Sc_d$  are the Prandtl and Schmidt number of the particle (determined in the numerical program from the film properties, see comments hereafter);  $FT$  and  $FM$  are the correction factors taking into account the increased fluxes (compared to Fick’s diffusion) due to the blowing effect (Stefan’s flux). These correction numbers are expressed in terms of the Spalding factors  $BT$  &  $BM$  defined as in Abramzon and Sirignano [11].

$$\begin{aligned}
Re_d &= |u_g - u_d| \rho_g \Phi_d / \mu_g \\
C_D &= 24 \left( 1 + 0.2 Re_d^{0.63} \right) / Re_d \\
Nu_d &= 2 + \left( \left( 1 + (1 + Pr_d Re_d)^{1/3} \right) Re_d^{0.077} - 2 \right) / FT \\
Sh_d &= 2 + \left( \left( 1 + (1 + Sc_d Re_d)^{1/3} \right) Re_d^{0.077} - 2 \right) / FM \\
FT &= \ln(1 + BT) (1 + BT)^{0.7} / BT \\
FM &= \ln(1 + BM) (1 + BM)^{0.7} / BM \\
BT &= Cp_d |T_d - T_g| / Lh_d \\
BM &= (y_{d,g} - y_{d,g\infty}) / (1 - y_{d,g})
\end{aligned} \tag{4}$$

Because of the low CPU time associated with the present approach (only one representative diameter is examined) the properties of both R134-A vapor and of the air entering in the Schmidt, Prandtl and Reynolds numbers are considered temperature dependent and established with a mass averaged formulation at a given mixing temperature (i.e. 1/3 rule for the film temperature of Yuen and Chen in[11]). All other vapor or gas properties are temperature dependent together with the latent heat of the refrigerant. For the thermo-dynamical properties of R134-A, data are extracted from Poling et al. [13] and/or the NIST web database. Our approach does not consider the internal flow inside of the droplet. The present authors are aware that such a simplification may be more adapted for a solid particle but is chosen here because the air velocity is not solved (1D approach). The set of pde’s (1) is solved numerically with a commercial Runge-Kutta 4 solver using a constant time step (named *rkfixed* in MathCAD 2001 Professional Software (©1986-2000 MathSoft, Inc.)).

### 3. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental installation allows the pressurization of liquid R134-A under different pressure values. The pressurized liquefied R134-A is stored at a pressure above its vapor pressure at the ambient temperature (i.e. 6.6 bars at 25°C). Nitrogen gas is introduced into the R134-A tank to control the driving pressure. A pressure transducer monitors the pressure history in the tube connecting the R134A and N2 tanks. At the connection with the R134-A tank, a two-entrance valve allows pressurization with N2 (in) and flow of R134-A (out) simultaneously. The liquid R134-A flows from the tank through a horizontal tube. At the end of this tube, a pneumatic ball valve system is installed and it is operated using pressurized air. A thermocouple is introduced in the tube to measure the temperature of the liquid R134-A before the exposure to the ambient. Different nozzle geometries can be mounted on the pneumatic valve.

A rack of 10 thermocouples with a distance of 0,05 m between each other was mounted in the downstream direction of the pneumatic valve in order to observe the axial temperature change at 10 different points simultaneously in time using a DAS16 acquisition system. The thermocouples give point measurements in the disintegrated part of the jet. The position of the first probe triggers the position of the so-called “flashing point” if this does not occur right at the nozzle exit. After this bursting point, the jet is totally disintegrated and an evaporating spray is observed. Nevertheless, present authors underline that without the triggering probe the position of the flashing point is case dependent and is highly sensible to the superheat level, pressure undershoot, depressurization rate and nozzle geometry ([1], [4],[5]). Moreover, measurements presented here are obtained for different distances between the first probe and the nozzle exit in order to observe whether the trend of the measured temperature was sensible to the modulation of the rack distance to the nozzle

### 4. RESULTS AND DISCUSSIONS

#### 4.1 Thermocouple measurements

The behavior of the flow under a driving pressure of 7 bars with 1 mm nozzle diameter is given on Fig. 1(left). The two firsts thermocouple supports appear as vertical white objects and their impact on the pattern of the flow is obvious. A representation of

the temperature evolution along the jet axis is given on Fig. 1(center) for jets exiting from 1 mm (left) nozzle. It can be noticed that the first measured temperature goes below the boiling temperature ( $T_{\text{boiling}} = -26.7^\circ\text{C}$  at 1 atm) and that the temperature reaches a plateau at about  $-55^\circ\text{C}$  far from the nozzle. It can be noticed that the comparison between the temperatures obtained with a rack of 10 thermocouples or the one given by a single thermocouple wire do not demonstrate high discrepancy, (i.e. low intrusiveness induced by the complete rack).

#### 4.2 Evaporation model prediction and comparison

On Fig. 1(right), a comparison of the measurements (symbols) obtained with 1 mm nozzle and the evaporation model (bold curve) prediction is displayed. The prediction given by the evaporation model is obtained for a set of initial parameters such as 25 m/s initial droplet velocity, 200  $\mu\text{m}$  of initial diameter and  $-20^\circ\text{C}$  initial droplet temperature. The ambient gas temperature is  $25^\circ\text{C}$  and is stagnant. The mass fraction at infinity is chosen as 0.2. A mixing rule constant of 1/3 is used. The general trend associated with the temperature decrease is in close agreement with the measurements. Nevertheless, this result is dependent on the set of initial values. Such sensibility is analyzed in the following paragraphs.

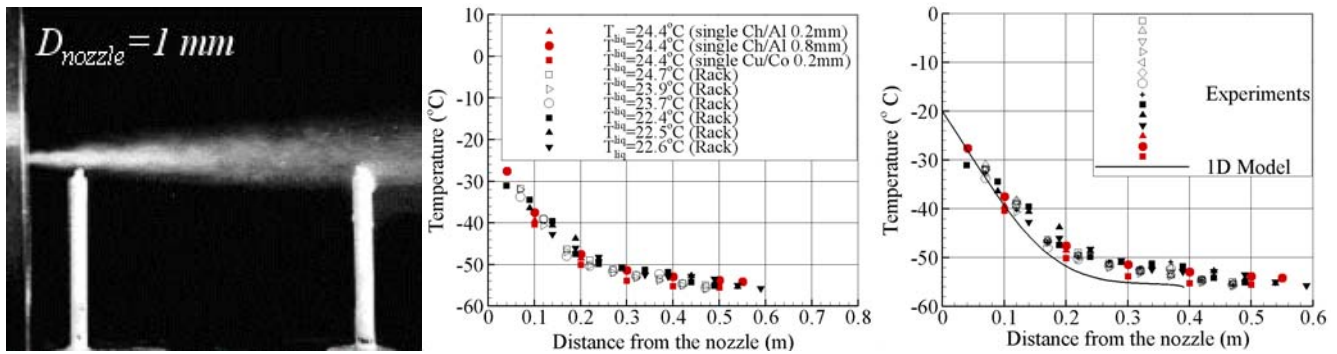


Fig. 1 (Left): The first two thermocouples in R134-A jet under 7 bars at  $22^\circ\text{C}$  for 1mm nozzle diameter; (Center): Temperature profiles for the jets issuing from 1 mm (Right) Comparison of temperature prediction with measurements of jets exiting a nozzle with a diameter of 1mm

On Fig. 2(left), a prediction of the droplet surface variation in time is displayed. It appears that there is no linear relation between the droplet surface decrease and the time when the droplet is not in a quasi-steady regime. It confirms that a quasi-steady hypothesis is required when the “ $D^2$  law” is used. On Fig. 2 (center), the history of the different relaxation times is presented and compared with the Stokes relaxation time. Based on this figure, it is found that the transfer of momentum is the fastest. The time relaxation associated with the transfer of mass is the slowest. The Stokes prediction and the relaxation time associated with momentum transfer coincide when the droplet enters in the Stokes regime (i.e.  $Re_p < 1$ ). This happens after 0.2 second or at a distance of about 0.39 meter from the nozzle. Fig. 2(right) displays the limited mass fraction of R134-A at the droplet surface. The mass fraction limitation is active only during the very first millisecond even when a time step as small as  $10^{-4}$  seconds was used (when an initial temperature of  $-20^\circ\text{C}$  was considered). It was found that the use of saturation pressure curve under pure equilibrium may lead to unphysical mass fraction when used in Eq. (3) (i.e. at  $20^\circ\text{C}$  using the equilibrium saturation pressure leads to a mass fraction of 1.3!).

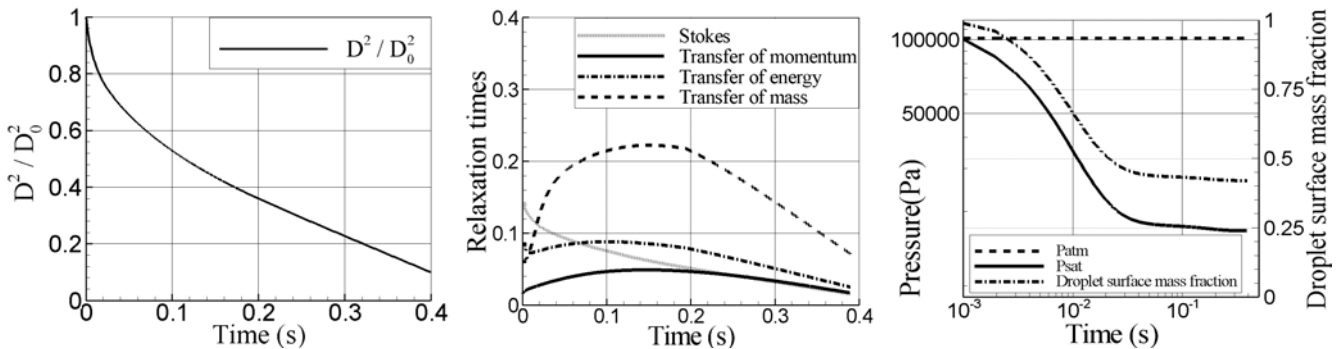


Fig. 2 (Left): History of surface evolution for the representative droplet; (Center): History of the relaxation times associated to the three transfer processes and compared with Stokes (Right): History of saturation pressure with Mass fraction of R134-A at the surface of the droplet

### 4.3 Model sensibility analysis

In the use of the evaporation model it has been found that the lowest value of the droplet temperature was very sensible to the mass fraction at an infinite distance of the droplet distance. A droplet in a pure fluid experienced a higher evaporation than a droplet in a surrounding fluid already containing traces of R134A as seen on Fig. 3(left). The spray influence was better taken into account with a value of the mass fraction at infinite distance of 0.2. This parameter proves to be crucial to follow the measured temperatures. On Fig. 3 (right) the droplet thermal inertia is displayed, with the bigger droplets keeping their temperature on a longer distance than smaller droplet. Therefore, the initial droplet diameter proves to be a major parameter when a correct slope of the temperature decrease is expected.

In the literature of evaporation models, one has to choose in between a rather large choice of correlations. The correlation used by [11] presents a coefficient  $Re_p^{0.077}$ . As it can be seen on Fig. 4(left), this coefficient is amplifying the decrease of temperature at high droplet Reynolds numbers but the temperature plateau is rather insensible to this coefficient. On Fig. 4 (center), the sensibility to the film temperature is displayed. A minor effect is noted between the use of no mixing temperature and a mixing temperature with a weighting factor of 1/3. Finally, a noticeable difference seems to lay in the choice of temperature dependent film properties when compared with the film properties fixed at the initial temperature (-20°C) all along the droplet path (Fig. 4(right)). This difference is higher than the experimental uncertainty and therefore should be taken into account when high temperature variations are expected.

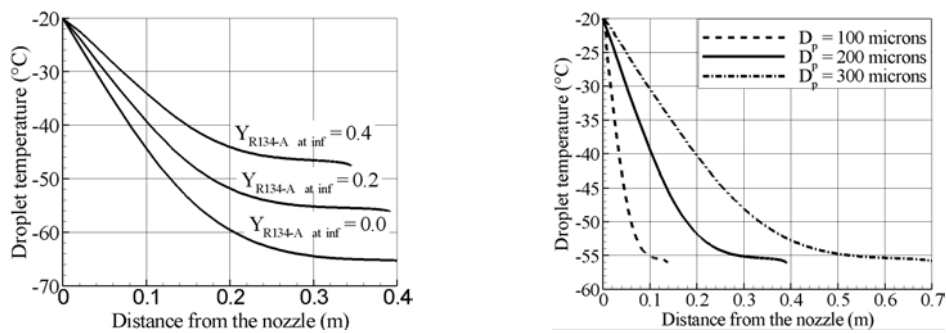


Fig. 3: (Left): Temperature sensibility to infinite distance mass fraction; (Right): Temperature sensibility to initial diameter

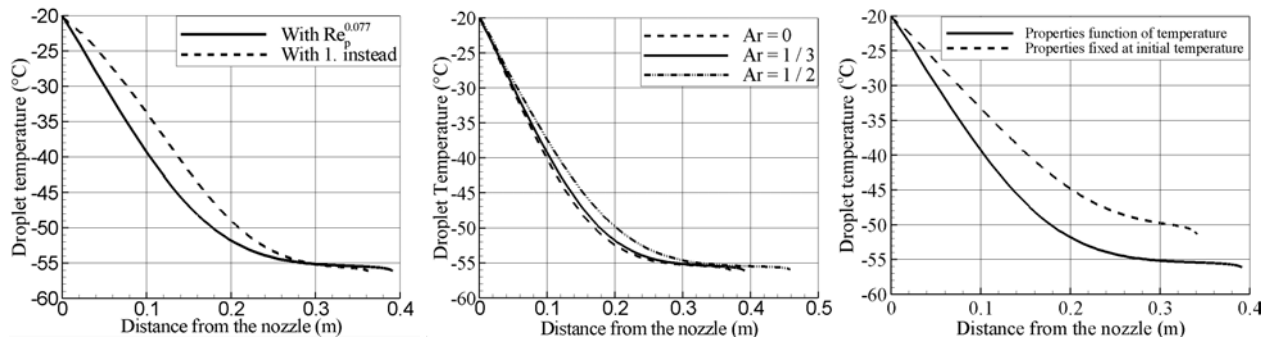


Fig. 4 (Left): Temperature sensibility to correction factor; (Centre): Temperature sensibility to mixing rule coefficient; (Right): Temperature sensibility to correlation

## 5. CONCLUSIONS

The temperature evolution of a flashing atomization is studied through thermocouple measurements. A high repeatability has been demonstrated during the measurement campaign. A rack of ten thermocouples was used at different initial distances from the nozzle. Measurements with a single thermocouple assess a low intrusiveness of the rack. A one-dimensional model taking into account the Stefan flow and the temperature dependent properties captures the overall trend of this temperature evolution. The plateau value of temperature is found to be highly sensible to the mass fraction at infinite distance from the droplet surface. Despite the metastable state of the liquid during the atomization, the use of the saturation pressure obtained at equilibrium gives a satisfactory trend if its values are limited by the ambient pressure to obtain mass fraction lower than the unity. On the numerical point of view of the model, sensitivity to parameters such as droplet diameter, mass fraction at infinite distance and temperature dependence for the film properties had been found important.

Further temperature measurements are currently planned together with Phase Doppler Anemometry to evaluate the impact of initial reservoir parameters such as initial liquid pressure and temperature on the joint evolution of droplet diameters and temperatures along the jet axis. This last measurement campaign will be useful to assess further the evaporation model.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of European Commission under the contract number EVG1-2000-22022 to undertake this research program.

## NOMENCLATURE

$BT, BM$	the Spalding factors
$C_D$	the droplet drag coefficient,
$C_{pd}$	the droplet heat capacity
$D_{d \rightarrow g}$	the mass diffusivity of R134A in air,
$FT, FM$	the correction factors taking into account the increased fluxes
$k$	the conductivity,
$L_{hd}$	the droplet latent heat
$M$	the molar mass.
$Nu_d$	the droplet Nusselt number
$Pr_d$	the Prandtl number of the particle
$Re_d$	the droplet Reynolds number
$Sc_d$	the droplet Schmidt number
$Sh_d$	the droplet Sherwood number
$u_d$	the velocity
$x_d$	the distance to the initial point
$y_{d,g}$	the mass fraction of R134-A in gas close to the particle
$y_{d,g\infty}$	the mass fraction of R134-A in gas at an infinite distance from the particle.
$\rho$	the volumetric mass,
$\mu$	the dynamical viscosity,
$\Phi_d$	the diameter
Indices like $_g$ and $_d$ are used for gas or droplet variables (or properties).	

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