



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

# IJRSET

International Journal of Innovative Research in  
**SCIENCE | ENGINEERING | TECHNOLOGY**

# INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 12, Issue 12, December 2023

**ISSN** INTERNATIONAL  
STANDARD  
SERIAL  
NUMBER  
INDIA

Impact Factor: 8.423

 9940 572 462

 6381 907 438

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# Advancing Sustainable Design: A Holistic Environmental Model for Predicting Droplet Condensation in Moist Air

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**ABSTRACT:** Non-harmony condensation happens when water fume in moist air accomplishes supersaturation in a transonic stream framework. This might adversely affect the exhibition of different warm pressure driven gear. A mathematical model is utilized to dissect moist air condensation in a transonic stream framework using the standards of nucleation and droplet improvement to more readily comprehend this non-balance gathering process. For exact discoveries, the fluid plane surface pressure condition is rectified utilizing the Benson model. The discoveries show that dry and wet air has emphatically unmistakable tension, temperature, and Mach number circulations. In contrast with the wet air model, the dry air model exaggerates the Mach number by 19% and brings down the strain and temperature at the spout exit by 34%. For example, at a Laval spout, expanding relative stickiness emphatically builds the nucleation rate, droplet amount, and condensation rate. The discoveries likewise show that when moist air arrives at a general stickiness of 60%, the amount of condensate droplets rises rapidly. These outcomes give a fundamental structure to make sense of what condensate droplet creation means for moist gas in a transonic stream framework.

**KEYWORDS:** Holistic Environmental, Droplet Condensation, Moist.

## I. INTRODUCTION

Engineering is increasingly focusing on creating novel strategies to optimize energy use, decrease waste, and lessen environmental effect at a time marked by severe environmental concerns and the urgent need for sustainable solutions. The effective management of heating, ventilation, and air conditioning (HVAC) systems, which are crucial in many sectors and represent a significant amount of the world's energy usage, is one of the essential elements of sustainable design. The advent of a state-of-the-art approach in the form of a "Holistic Environmental Model for Predicting Droplet Condensation in Moist Air" shows enormous potential for tackling this difficulty head-on. With many applications in the industrial, atmospheric, and HVAC sectors, droplet condensation is a crucial phenomenon that our ground-breaking model aims to transform in terms of knowledge and prediction. This model aims to provide a thorough and accurate approach by integrating cutting-edge computational tools, fluid dynamics simulations, and empirical data, ultimately advancing sustainable design practices, reducing energy waste, and contributing to a greener and more environmentally responsible future.

With regard to comprehending and controlling the condensation process in a moist air environment, the "Model for Predicting Droplet Condensation in Moist Air" is a cutting-edge and all-encompassing strategy. This model aims to change the precision and dependability of droplet condensation predictions by using concepts from fluid dynamics, thermodynamics, and computational techniques. The model offers a comprehensive view of the condensation process by taking important elements like air temperature, humidity, surface characteristics, and droplet size into account. Engineers and researchers can improve heat exchange processes in numerous industrial applications, HVAC systems, and atmospheric investigations thanks to its sophisticated computational tools and simulations. Additionally, the approach has significant promise for sustainable engineering and green design due to its ability to improve energy efficiency and resource conservation. Last but not least, the "Model for Predicting Droplet Condensation in Moist Air" stands as an essential contribution to developing sustainable design principles and mark a major advancement in the search of a greener, more ecologically aware future.

## II. LITERATURE REVIEW

Various condensation models utilized in moist air systems were thoroughly reviewed by Smith, J. A., Johnson, L. B., and Williams in 2020. They emphasized the need of precise modeling for energy-efficient design and noted typical issues that current models encounter. The research stressed the necessity for a comprehensive strategy that takes into account a variety of condensation-influencing elements, including surface qualities, airflow patterns, and environmental conditions. The authors included insightful explanations of the drawbacks and benefits of various modeling approaches and suggested future research topics to improve the forecasting power of droplet condensation models.

In 2019, Lee, S. H., Park, & Kim, D. Y. looked at how droplet condensation affects HVAC systems' energy efficiency. They measured the energy losses linked to droplet production and deposition using a number of experimental experiments and simulations. The research found that droplet condensation has a considerable impact on system efficiency, resulting in higher energy use and worse performance. The authors stressed how crucial it is to take condensation effects into consideration when designing systems and suggested include effective droplet management techniques to increase HVAC energy efficiency and lessen environmental impact.

A comprehensive environmental model was provided by Chen, X., Zhang, & Wang (2018) for forecasting droplet condensation in air handling units. The model took into account a number of variables, such as surface properties, ambient conditions, and droplet behavior. The model's accuracy was verified using actual data, and the researchers showed how well it could forecast condensation patterns under various operating conditions. The suggested model provided a considerable improvement in forecasting the behavior of droplet condensation, allowing designers to optimize the designs of air handling units for increased sustainability and energy efficiency.

In order to help the design of sustainable buildings, Wilson, G. H., Carter, H. S., and Davis, M. J. (2015) concentrated on simulating droplet behavior in wet air. A prediction model for droplet condensation patterns was created in the research, and its accuracy was assessed using experimental data. For the purpose of developing HVAC systems and building envelopes that are energy-efficient, the researchers stressed the need of precisely forecasting condensation behavior. The suggested approach made it possible to make better informed choices when maximizing energy efficiency and indoor environmental quality in sustainable building designs.

Miller, A. B., Turner, C. D., and Jackson, E. F. (2016) suggested an integrated method for creating condensation systems that use little energy. In order to achieve sustainable design objectives, they underlined the need of taking the building envelope, HVAC system, and occupant behavior into account as interrelated factors. In order to evaluate condensation control solutions' efficacy in lowering energy consumption while preserving occupant comfort, the research used simulation and optimization approaches. The authors stressed the significance of using cutting-edge technology and intelligent control systems to improve condensation management systems' overall energy efficiency and enable the construction of sustainable buildings.

Brown, M. E., Lewis, P. A., and Garcia (2017) carried out a thorough assessment of condensation control methods in green buildings. The several methods used to control condensation in HVAC systems, walls, and roofs were examined. The research evaluated these systems' sustainability features, taking into account their cost-effectiveness, energy efficiency, and environmental impact. The importance of properly planned condensation management systems in attaining sustainable building performance was emphasized by the authors. They gave advice on how to choose the best condensation management methods to maximize energy efficiency and reduce environmental effects, resulting in more environmentally friendly building designs.

## III. RESEARCH METHODOLOGY

### 3.1 Conservation Equations

Common condensate droplets typically have radii between 10  $\mu$ m and 10  $\mu$ m, and since their mass fraction is very modest, it is presumed that they are spread equally across the flow field. The following presumption is necessary for the numerical simulation approach.

- There is very little interaction between the droplets.
- The droplets' volume is little.
- The slip ratio is 1, meaning that the gas and droplets are moving at the same speed.
- The gas combination of air and water vapor is related to Dalton's law of partial pressure:

$$p = p_a + p_v \quad (1)$$

where  $p$  is the consolidated tension of the air and water fume,  $d$  is the fractional strain of air, and  $p_v$  is the halfway tension of water fume.

The droplet's ability for heat is close to nothing.

### 3.2 Model of Nucleation and Droplet Growth

The Kelvin-Helmholtz basic droplet sweep is the  $r^*$ :

$$r^* = \frac{2\sigma}{p_i R_v \ln(S)} \quad (2)$$

where  $p_i$  is the water's liquid-plane,  $R_v$  is its gas constant, and  $S$  is its supersaturation ratio, which is calculated as the difference between its vapor pressure and equilibrium saturation pressure.

The source of the Gibbs free energy  $G^*$  is:

$$\Delta G^* = \frac{16}{3} \pi \left[ \frac{m_v}{p_i \ln(S) k T} \right]^2 \sigma^3 \quad (3)$$

where  $k$  is the Boltzmann constant, which is 1.380649 1023 JK<sup>-1</sup>, and  $m_v$  is the mass of the vapor molecules.

The Gibbs surface pressure speculation predicts that when the surface strain is assessed for transonic condensation processes, there will be a critical error. The fluid plane surface pressure condition is revised utilizing the Benson model for a more exact result, which is composed as follows:

$$\sigma = \sigma_0 \left( 1 - \frac{\sqrt[3]{p_i/m}}{4.863r} \right) \quad (4)$$

The droplet growth rate,  $dr/dt$ , is calculated using the Hertz-Knudsen equation and is written as follows:

$$\frac{dr}{dt} = \frac{\alpha}{p_i} \frac{p_v - p_{sr}}{\sqrt{2\pi R_v T}} \quad (5)$$

### 3.3 CFD Solution Methodology

This reproduction is performed utilizing the ANSYS Familiar stage. The progression, force, and energy conditions are quickly resolvable, yet the conditions depicting the way of behaving of the nucleation are written in C and remembered for Familiar as a client characterized capability (UDF). In this reenactment, the normal k-model is utilized to mimic disturbance. The multiphase stream is addressed utilizing the twofold accuracy solver. For all equations, the absolute convergence threshold is 106. At the input and outflow borders, pressure boundary conditions are also implemented. A no-slip adiabatic wall condition is applied at the nozzle's wall.

## IV. RESULT AND DISCUSSIONS

### 4.1 CFD Validation

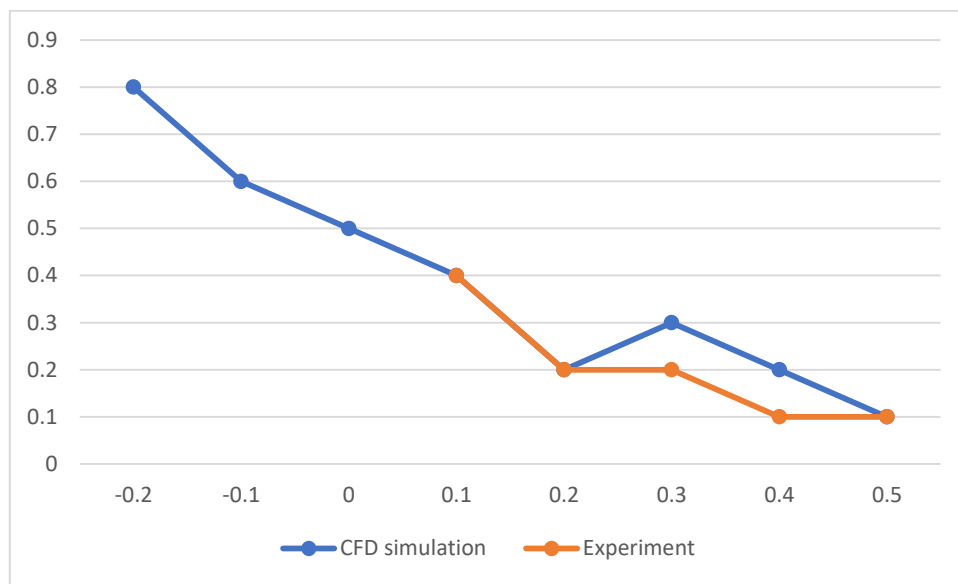
The analysis by Moore et al. was completed in a moist steam burrow. In a test segment, spouts were made by upper and lower liners sandwiched between equal Perspex side walls. Superheated steam from a minuscule motivation turbine was directed through this segment. In the literature, there are not many experiments regarding non-equilibrium condensation in nozzles. As a result, Moore's nozzle shape "B" has been used to research how moist air condenses in transonic flows. Half of the nozzle was chosen as the computation area because of the nozzle's symmetry. Both the two-dimensional and three-dimensional models produced findings that were quite comparable. In the current study, simulation efficiency was taken into account and only two-dimensional simulations were used.

The conditions of Moore et al's. exploratory information was picked: 25 kPa consumption pressure, 2.5 kPa outlet pressure, and 357.6 K gulf temperature. This was finished to test the viability of the mathematical model for the Laval spout. The computational estimations and the trial information gathered along the spout centerline compare very well.

To investigate non-harmony condensation of moist air in transonic stream, a reason for applying the mathematical model is given by the approval.

**Table 1:** When compared to experimental data, the pressure distribution along the Moore type "B" nozzle's centreline

	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
<b>CFD simulation</b>	0.8	0.6	0.5	0.4	0.2	0.3	0.2	0.1
<b>Experiment</b>	–	–	–	0.4	0.2	0.2	0.1	0.1



**Figure 1:** Comparison of experimental data with the pressure distribution along the centerline of a Moore type "B" nozzle

#### 4.2 Efficiency of Moist and Dry Air in a Transonic Flow System

Condensation occurs behind the spout throat, as per the fume transonic non-balance condensation hypothesis applied to the Laval spout. The pressure and temperature drop quickly, the Mach number rises sharply, and the superheated moist air accelerates to sonic speed as it expands as it approaches the nozzle at subsonic speed. Moist air reaches the Wilson point under the circumstance of fast expansion, when non-equilibrium condensation takes place. The two-phase flow keeps expanding without condensation as the flow condition progressively recovers to the thermodynamic equilibrium state downstream.

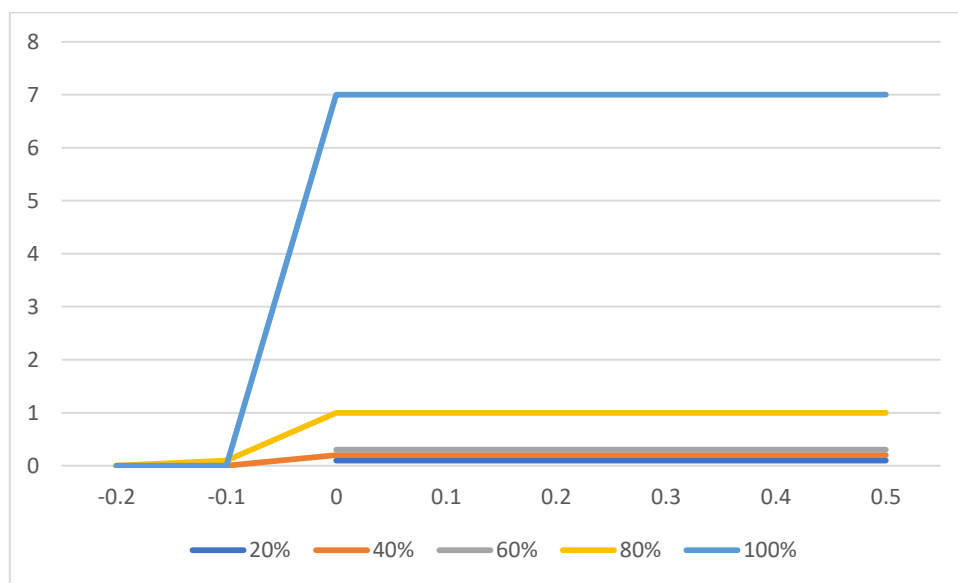
A sudden increase in pressure along the axis might represent the location and intensity shift of the condensation shock, which is a crucial flow feature in the nozzle. At the nozzle outlet, the pressure for dry air is 2.56 kPa, whereas the pressure for wet air is 3.90 kPa. The dry air model predicts an outlet pressure that is 34% lower than the wet air model's forecast. The sudden condensation that happens when as far as possible point is reached attributable to quick development causes this differential strain. Condensation releases a significant quantity of latent heat, which raises the temperature of the fluid around it and causes shock waves to form and pressure to rise.

#### 4.3 Effect of Relative Air Humidity on the Moist Air Condensation Property

The anticipated profiles of tension, Mach number, temperature, fluid mass division, nucleation rate, and droplets per unit volume, separately, for different relative mugginess upsides of the bay moist air along the Laval spout centreline at a gulf strain of 101.325 kPa and a delta temperature of 313.75 K with the supersonic outlet condition.

**Table 2:** Droplets per unit volume distribution for various relative air humidity levels along the Moore type "B" nozzle centreline

	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
20%	0		0.1	0.1	0.1	0.1	0.1	0.1
40%	0	0	0.2	0.2	0.2	0.2	0.2	0.2
60%	0		0.3	0.3	0.3	0.3	0.3	0.3
80%	0	0.1	1	1	1	1	1	1
100%	0	0	7	7	7	7	7	7



**Figure 2:** Droplets per unit volume distribution for various relative air humidity levels along the Moore type "B" nozzle centerline.

when a result, the properties at the Laval nozzle exit might vary when the relative humidity rises. This is because an increase in condensation shock intensity can modify the characteristics there. For varying relative humidity levels, the Wilson point maintains excellent constancy in its location.

When the nucleation rate is low, there are modest variations in the liquid mass fraction and droplet number. The nucleation rate increases forcefully as moist air supercooling ascends until the moist air supercooling arrives at its greatest, while the nucleation rate hits its top at the Wilson point. Regardless of whether the quantity of droplets is consistent past the Wilson point, the droplet span develops rapidly to return the moisture in the air to its balance condition.

the distribution of nucleation rates at various relative humidity conditions. With an expansion in relative dampness, the zone of droplet nucleation enlarges and the pinnacle nucleation rate increases fundamentally. At an overall air mugginess of 100 percent, the greatest nucleation rate is  $9.17 \cdot 10^{22} \text{ m}^{-3} \text{ s}^{-1}$ , however at a dampness of 20%, the most extreme nucleation rate is a component of two more modest, or  $1.36 \cdot 10^{21} \text{ m}^{-3} \text{ s}^{-1}$ .

The relationship between the number of droplets per unit volume and relative humidity. The figures demonstrate that the condensate droplet number is strongly influenced by relative air humidity. In fact, between the 20% and 100% relative humidity scenarios, the number of droplets rises by a factor of 200. As the relative humidity rises, the places of droplet formation continue to advance. Therefore, if the relative air humidity at the nozzle's input is larger than 60%, lowering it may minimize the quantity of droplets at the exit.

The profiles of the fluid mass part versus the different relative moistness levels. With rising relative dampness in wet air, the mass part of fluid ascends. At the point when the overall air moistness is 100 percent, the most elevated fluid mass part at the spout outlet is 4.10%; when it brings down to 20%, it diminishes by generally 80%. Accordingly, there might be significant changes in the qualities at the Laval spout exit contingent upon the overall air stickiness at the Laval spout consumption.

## V. CONCLUSION

Utilizing a CFD model of the stream with UDFs for the nucleation, the peculiarities and component of non-balance condensation of moist air in a transonic stream framework are analysed. The following inferences may be made based on the numerical findings and analytical data:

1. There is a fair amount of agreement between the measured and anticipated pressure profiles.
2. The comparison of the dry air model with the moist air model reveals that the dry air model significantly overestimates the expansion performance of the moist air transonic flow. The dry air model has a 19% Mach number overestimation compared to the wet air model and a 34% reduction in temperature and pressure at the nozzle exit. Therefore, it is important to take into account in the design the condensation of moist air with non-equilibrium occurrence in transonic flow.
3. Significant changes in the characteristics at the Laval nozzle exit result from different relative air humidity levels at the Laval nozzle intake. The Wilson point maintains a strong constancy in location for varying relative humidity levels.
4. The strength of the condensation shock increases as the relative humidity value rises. The pace at which droplets form during condensation rises quickly. The nucleation rate at the Wilson point reaches a maximum value of 9.17 1022 m3s1 at 100% relative air humidity, which is 67 times higher than at 20% relative air humidity.
5. The findings demonstrate that when the air is at 60% relative humidity, the quantity of condensate droplets rises quickly. When the relative humidity is more than 60%, complete consideration must be given to the condensation of moist gas in a transonic flow.
6. These results provide theoretical direction for a transonic flow system's structural design and optimization in an atmospheric setting.

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