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Modelling of Droplet Evaporation in Humid Gas with Algebraic Heat and Mass Transfer Models

Dipartimento di Ingegneria Industriale DII
Corso di Laurea Magistrale in Energy Engineering

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2023 - 2024

Declaration of Authorship

I, Mohit Narula, declare that this thesis titled, 'Modelling of Droplet Evaporation in Humid Gas with Algebraic Heat and Mass Transfer Models' and the work presented in it are my own.

I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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Abstract

The study focuses on advancing the understanding of droplet evaporation in humid gas environments through the utilization of the LibHuAir Xiw library and a constant property model. LibHuAir Xiw provides instrumental in enhancing the precision of modeling and simulation, offering a suite of tools for tasks such as heat and mass transfer calculations in humid conditions and determining thermodynamic properties. The integration of this library marks a pivotal step toward achieving the study's objectives. The investigation begins by emphasizing the significance of studying single droplet evaporation as a foundational step for comprehending the broader evaporation process. Droplet evaporation, a fundamental phenomenon occurring when a liquid droplet is exposed to a gas environment, is explored in-depth. The study delves into the intricacies of mass transfer, vaporization, and diffusion, crucial processes governing droplet evaporation in various scientific, industrial, and natural contexts. The constant property model is introduced to simplify the understanding of droplet evaporation, incorporating key parameters such as droplet radius and Spalding mass transfer number. The model considers the dynamic equilibrium between vapor molecules diffusing outward and those from the liquid phase, contributing to a sustained and controlled evaporation rate over time. Energy exchange and its relationship with heat transfer during droplet evaporation are discussed, highlighting the absorption of latent heat of vaporization from the surroundings, resulting in a reduction in droplet temperature. The model's evaluation involves considering factors like the droplet evaporation rate, diffusion coefficient, and Spalding mass transfer number. The study employs the constant property model to simulate droplet evaporation over time, showcasing a graphical representation of droplet radius. To validate the constant property model, comparisons are made with experimental data from Ranz and Marshall (1952), demonstrating a close match between the model's simulation and the experimental results. The adaptation of the linear graph to a nonlinear representation facilitates a thorough understanding of the model's performance, emphasizing its efficency.

Universität Duisburg – Essen
Campus Duisburg

Fachbereich Ingenieurwissenschaften – Abteilung Maschinenbau

Task Description - Master Thesis

Modelling of droplet evaporation in humid gas with algebraic heat and mass transfer models

Turbocompressors are part of systems to transport hydrogen, generate electricity with a heat engine, or create new products. Cooling the working fluid, primarily gas, before or in the compressor is beneficial to reduce the compression work, increase the power output of heat engines or avoid polymerisation. Different cooling concepts such as interstage cooling and evaporative cooling are available. The aim is to approximate an isothermal compression process. Evaporative cooling can be realised by injecting a liquid in the form of droplets into the gas stream. The droplets either evaporate completely before the stages or also move through the stage and continue evaporation there. Models are required to understand and optimise the process, especially for the evaporation of the droplets. These droplet evaporation models are heavily dependent on empirical data. Restrictions of the models, for example expressed by Stokes- or Reynolds-Number, must be known. Experimental validation and plausibility checks are mandatory.
The results of this Master's thesis are to be cast into a computer program that allows the calculation of evaporation times by a number of user inputs such as inlet temperature, inlet pressure, and droplet diameter. Further, comparing the calculated results against experimental values shall be a build-in function.
The scientific part of this Master's thesis is intended to pave the way for the coding of this computer program. A literature study shall reveal available evaporation models and validation cases. A thorough analysis of the models shall be conducted. The assumptions leading to the models and the resulting limitations shall be explored. The different models shall be compared with each other. The models shall be critically assessed against the principles of heat and mass transfer.

The thesis can be divided into the following tasks:
- Literature study on available models
- Literature study on validation cases (experimental studies on droplet evaporation)
- Analysis of the models regarding effects covered, reliability, justification of simplifications
- Development of a computer program to evaluate the models
- Comparison of computer (model) results with experimental results
- Analysis of the results

The work is to be carried out in close cooperation with the Chair of Turbomachinery.

The student grants permission to publish the title of the thesis together with his/her name on the website of the Chair of Turbomachinery and in the Alumni-Newsletter of the faculty (www.uni-due.de/tm).

Die Betreuerin/der Betreuer/the supervisor

Die Studentin/der Student/the student

Prof. Dr.-Ing. Dieter Brillert
Chair of Turbomachinery

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Grazie

Padova, December 2024

Mohit Narula

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Chapter 1

Introduction

1.1 Background and Motivation of the Work

Water injection in gas compression operations has grown considerably in recent years, driven by the need to improve machine performance, and has been performed through a variety of methods. The growing interest stems mostly from the power generation industry, where water injection is used in gas turbines to minimize compressor power consumption and increase the overall power production and also by increasing mass flow in the turbine section.

In the context of gas compression, the term ”wet compression” broadly defines the flow of a two-phase mixture of liquid water and gas. During the operation, small water droplets are injected into the air stream, and as they evaporate, they create a cooling effect that mitigates the temperature rise throughout the machine. The presence of this two-phase fluid affects both the compression process and the overall performance of the compressor.

Numerous studies have been conducted to gain a deeper understanding of the issue which involves analytical, computational, and experimental investigations. These studies focused on examining the thermodynamic and aerodynamic effects of water injection. In addition to providing general insights into the effectiveness of wet compression processes, these works also highlight the impact of factors such as the amount of water injected, droplet size, water quantity, etc.

In various industrial and environmental processes such as spray drying, combustion, and atmospheric research, the evaporation of droplets plays an important role. Understanding the behavior of droplet evaporation in humid gas environments is very important to optimize these processes and predict their environmental impact. Hence, the development of accurate and efficient mathematical models for droplet evaporation is of utmost importance.

1.2 Objectives

The main goal of this thesis is to create and test algebraic heat and mass transfer models for the evaporation of droplets in humid gas environments. The following list includes the list of goals:

- Investigate the existing literature on droplet evaporation and identify the limitations of current models.
- Develop a comprehensive understanding of the underlying mechanisms governing droplet evaporation in humid gas.
- Validate the proposed models using experimental data and compare their performance against existing models.
- Development of a computer program to evaluate the models.
- Comparison of computer (model) results with experimental results.
- Analysis of the results.

1.3 Scope and Limitations

The development of algebraic heat and mass transport models is notably covered in this thesis's study of droplet evaporation in humid gas settings. The impacts of variables including droplet size, gas temperature, humidity, and composition will be considered by the models. The algebraic models will not, however, explicitly consider some difficulties, such as non-uniform temperature and concentration gradients inside the droplet.

Furthermore, while the proposed model's main goal is to capture the fundamental aspects of droplet evaporation, they may have limitations in certain extreme or specialized conditions. It is really important to recognize these limitations and consider further refinements or alternative approaches in such cases.

1.4 Significance of Study

The development of Improved and efficient algebraic models for droplet evaporation in humid gas environments has great practical implications. Engineers and scientists will benefit from these models as they provide improved tools for optimizing industrial processes, including droplet evaporation, ultimately leading to improved efficiency and productivity. Moreover, these models will contribute to the advancement of science by aiding in the understanding and prediction of a gaseous suspension of tiny solid or liquid particles behavior as well as its help in understanding cloud formation.

Furthermore, the findings of this study will serve as a foundation block for the development of more comprehensive numerical simulations and computational fluid dynamics models, facilitating further research in related fields.

Chapter 2

Wet compression

The injection of liquid water in the air intake system is a well-known method for performance enhancement in gas turbines and aerodynamic engines. The use of this technique has been evolving throughout the last 75 years, changing its features and applications. An overview of its development in the past is presented in the following sections of the chapters.

2.1 History of Water Injection

The idea of water injection for system power enhancement was already developed in the early years of gas turbine technology. Because of the lack of adequate liquid injection technology, the applicability of this method was entirely limited or restricted to short-term use; indeed, droplets exceeding a certain size and the formation of liquid phase sheets may lead to unacceptable erosion on the blades. Further work was made with military aviation development and then transferred to civil aviation in 1950 since compressor water injection was used to generate temporarily increased thrust during aircraft starting at high ambient temperatures or high altitudes. The liquid phase injected was often a mixture of de-mineralized water and methanol.[1]

Research papers from National Advisory Committee for Aeronautics (NACA) investigated the application of water injection on axial flow compressors in gas-turbine engines, observing lower specific work and higher compression ratios in the machine.[2]]. Beede et al.[3] conducted an analysis of the performance of a

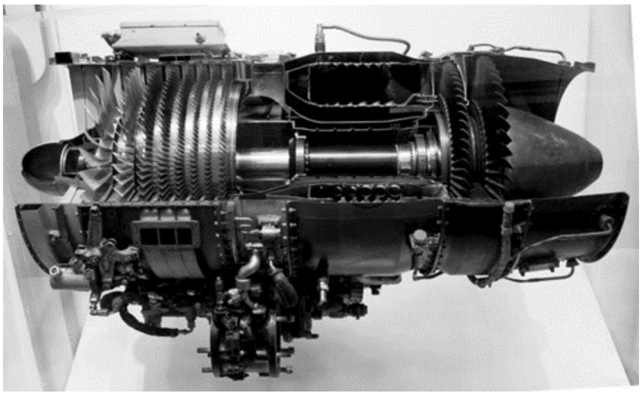

Figure 2.1: 1950 Axial Compressor

centrifugal machine, in which increasing water-air ratios were tested, showing an increase in total pressure ratio and air mass flow, and a reduction in efficiency as well. Therefore, interest in wet compression has been mainly in axial and centrifugal machines since the first application steps of the technology.

Further development of injection technology was achieved in several industrial branches until the 1990s. The growth of the worldwide energy market and the associated energy cost led to the rediscovery of the method of water injection for power boosting in stationary gas turbines. The need for cost-effective long-term water injection systems to employ in the intake sections of gas turbines increased the publication of research work, focusing on one side on the size of the droplets suitable to avoid erosion phenomena and keep maintenance costs reduced, and on the other side on the amount of water to get efficient evaporation through the machine.

Therefore, due to the increasing energy demand in emerging markets, where higher ambient temperatures are common and climate conditions imply the coupling between phases of highest power demand and highest temperature, the research work increased significantly around 2000 to investigate the use of liquid phase injection in stationary gas turbines. In this section, we describe the fundamental concepts underlying droplet evaporation and the heat and mass transfer processes. Concepts such as diffusion, evaporation rate equations, and the role of humidity are explored here in detail. Theoretical frameworks and mathematical formulations important to droplet evaporation modeling are discussed, with an emphasis on algebraic heat and mass transfer models.

2.2 Recent research works on the topic

The amount of papers published in the last decade shows interest in this technique. Many different aspects related to multiphase flow in compressors have been investigated, in search of deeper knowledge and a deeper understanding of the complex phenomena associated with wet compression.

An overview of the droplet evaporation models, including empirical and mathematical models. These models' strengths and limitations are carefully examined, demonstrating how useful they are in capturing the intricacies of droplet evaporation in humid gas environments. The evaluation also considers the added advantage of humidity effects in existing models and highlights any key discrepancies or shortcomings in current research.

2.2.1 General Advances in axial compressors investigation

Among the research efforts, most of them consider the effects of water injection on axial compressors, as its use is intended to boost the power output of gas turbines. Although they refer to different machines from the one that has been investigated in this work, their contribution to the knowledge of the topic is important and deserves to be mentioned.

Zheng et al[4]. have proposed a thermodynamic model of the wet compression process, in which several aspects such as the ideal wet compression process, actual wet compression process characteristics, water droplet evaporation rate, wet compression work, and compression efficiency are discussed. The results show that the reduction of compression work can be reduced and is lower than that of a dry air isentropic process, and therefore a new wet compression efficiency is proposed to evaluate the performance. Evaporative rate, time, and aerodynamic breaking of water particles have proven to be important for wet compression.

The impact of evaporate processes on compressor operation has been examined by White and Meacock, focusing particular attention on cases with substantial over-spray, where significant evaporation takes place within the compressor itself rather than in the inlet (inlet fogging). This work describes a simple numerical method for computation based on a combination of droplet evaporation and mean line calculations, and this method is applied to a generic compressor geometry to investigate the off-design behavior that results from evaporative cooling.

Bharghava and Meher-Homji[5] developed an analysis of the effects of inlet fogging on a wide range of existing gas turbines, considering both evaporative and overspray fogging conditions, and showed a correlation between performance and gas turbine key design parameters due to inlet fogging effects. Moreover, a sensitivity study has been carried out to examine the effects of varying climatic conditions and to see if the general qualitative trends noted are modified.

Among the latest work on water injection in axial compressors, Schnitzler et al.[6] investigated numerically and experimentally the effects of water droplets on the operating behavior of a four-stage axial compressor. Increased mass flow is assessed. Negative effects on global performance occur for a water-air mass ratio of 2 %, with a lower pressure ratio and mass flow values, compared to the dry case.

2.3 Experimental studies and Data Analysis

Experimental studies have been conducted to investigate the complex phenomenon of droplet evaporation in humid gas environments.

Ranz and Marshall (1952) conducted experimental studies to investigate the complex phenomenon of droplet evaporation in humid gas environments. Their work laid the foundation for understanding the fundamental mechanisms involved in droplet evaporation and provided valuable insights into the behavior of droplets in various applications, including industrial processes, combustion, and atmospheric sciences.

In their experiments, Ranz and Marshall examined the evaporation of liquid droplets in a controlled environment where the surrounding gas had a known humidity. They carefully measured the evaporation rates of droplets of various sizes and materials, and systematically varied parameters such as temperature, humidity, and airflow velocity.

One of the key findings of Ranz and Marshall's studies was the establishment of empirical correlations for the evaporation rates of droplets. They proposed dimensionless groups, such as the Sherwood number, which relates the mass transfer coefficient to the droplet size, gas properties, and operating conditions. These correlations have since been widely used in the engineering and scientific communities to estimate droplet evaporation rates in practical applications.

Furthermore, Ranz and Marshall's work also provides insight into the influence of various factors on droplet evaporation. They observed that the presence of humidity in the gas environment affects the evaporation process significantly. Humidity affects the concentration gradients at the droplet interface and also affects the diffusion rates of water vapor, leading to changes in evaporation behavior.

Overall, Ranz and Marshall's (1952)[7] experimental studies on droplet evaporation in humid gas environments played a crucial role in advancing our understanding of this complex phenomenon. Their findings and correlations 2.2 have provided valuable tools for engineers and researchers working in fields where droplet evaporation is a critical process, enabling more accurate predictions and optimization of various applications involving droplets. Experimental results are going to be used in model validation.

2.4 Inlet fog boost

Inlet fog boost refers to a specific technique that is used in industrial systems, gas turbines, to improve the performance or efficiency of combustion engines. This technique involves the injection or introduction of a fine mist or fog into the inlet or intake air stream before it enters the combustion chamber or air compressor. Typically injection rates are approximately 1%by mass and droplet sizes are generally greater than 10 μm in diameter. These relatively large droplets do not evaporate very quickly and will experience significant slip relative to the flow, thus tending to be centrifuged toward the compressor casing. The main benefit derived from IFB is the reduction in the inlet air temperature [8].

Zhluktov et al[9] have also computed wet compressor characteristics, using a one-dimensional numerical method with;1%inlet fog. Their calculations take into account a wealth of two-phase phenomena, including droplet centrifuging, film formation, and film evaporation. On the contrary, his work is restricted to small droplets that follow the gas-phase velocity with negligible slip.

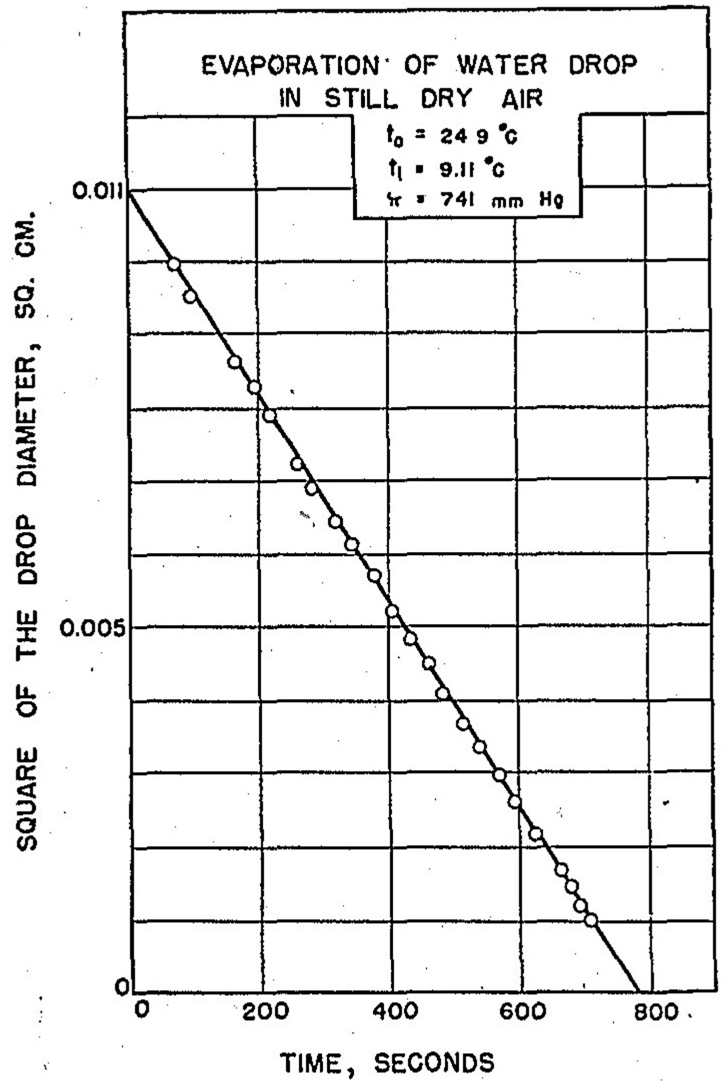

Figure 2.2: Square of Droplet Diameter vs Time

2.5 Evaporation of a Single Droplet

The thermodynamic analysis of Droplet Evaporation requires the definition of some parameters used in the investigation. Before introducing the model, a brief description of these parameters is presented.

2.6 Principle of the single droplet in humid air

When a single droplet of liquid, such as water, is suspended in a gaseous environment with varying levels of humidity, several factors come into play that influence the behavior of the droplet, such as

- **Humidity**: Humidity refers to the amount of water vapor present in the air. The rate of evaporation and condensation of the droplet's surface is influenced by the concentration of water vapor surrounding it. It is commonly stated as a percentage of relative humidity, which is nothing but the ratio of the actual quantity of water vapor in the air to the maximum amount it can hold at a particular temperature.
- **Temperature**: Temperature is very important in the evaporation and condensation processes. Higher temperatures often result in much faster evaporation, but lower temperatures might result in condensation of water vapor onto the droplet surface.
- **Droplet Size and Shape**: The size and shape of the droplet have a considerable impact on how it behaves in humid air. Because of their higher surface area-to-volume ratio, smaller droplets evaporate faster than bigger ones. The droplet's shape can also affect its evaporation rate, leading to faster evaporation if it is small.
- **Saturation**: When the air around a droplet achieves its maximal value of water vapor-holding capacity, the rate of evaporation equals the rate of condensation, this is referred to as saturation. The droplet is considered to be in balance with the surrounding air at this moment.
- **Evaporation and Condensation**: When a droplet is exposed to humid air, it constantly loses water molecules as a result of evaporation. If the air surrounding the water vapor is not saturated, water vapor from the surrounding air can condense onto the droplet's surface at the same time.
- **Equilibrium**: A single droplet in humid air tends to establish an equilibrium condition where the rates of evaporation and condensation become equal with respect to time. The size of the equilibrium droplet and the surrounding humidity level are affected by some environmental factors such as temperature and humidity.

The droplet's interaction with the surrounding air is dynamic and driven by the difference in vapor pressure between the droplet's surface and the air. As the droplet evaporates, it cools, which impacts the humidity and temperature of the surrounding air, causing variations in the droplet's evaporation rate.

Understanding the principle of single droplets in humid air is important for a variety of applications such as cloud physics, climate modeling, and aerosol formation in research. It helps scientists and researchers forecast and explain processes including cloud formation, droplet development, and the function of aerosols in the atmosphere.

2.6.1 Influence of Air on droplet

The exchange of a single droplet of humid air with its surrounding air can have an impact on heat and mass transfer processes. The behavior of the droplet and the resulting transfer effects are influenced by factors such as its size, temperature, relative humidity of the air, and the velocity of the surrounding airflow.

- **Evaporation & condensation**-If the temperature of the droplet is higher than the dew point (the point at which the air becomes saturated) the droplet is going to evaporate. When the droplet evaporates, it releases some moisture within the air, leading to increasing humidity. The droplet and the surrounding air are both cool as a result of this process. In contrast, condensation will occur if the air is cooler than the air and the droplets grow in size by absorbing moisture from the air.
- **Mass Transfer**-The mass transfer with the droplet is influenced by the quantity of water vapor present in the air. When air is more humid than the air surface, water molecules tend to diffuse from the air to the surface of the droplet, resulting in condensation. If the air is drier than that of the droplet, the droplet will evaporate and lose water molecules with the surrounding air.
- **Heat Transfer**-The temperature of the droplet affects the heat transmission with the air. Heat will move from the droplet surface to the surrounding air via conduction or convection if it is drier than the surrounding air. As a result, the droplet cools as the air around it dries. Heat passes from the air to the droplet if the droplet is colder than the air.

2.6.1.1 Mass Transfer

Mass Transfer is nothing but the movement of substances from one region to another. It occurs due to concentration differences between regions and is driven by diffusion and advection.

- **Diffusion**-The transfer of the molecules from a high concentration area to a low concentration area is referred to as diffusion. This procedure attempts to balance the concentration throughout the system. In gases and liquids, molecules move arbitrarily, interacting and spreading out until equilibrium is reached.
- **Advection**-The bulk movement of a material with the flow of a fluid is referred to as advection. Advection as opposed to diffusion. Advection can be seen in the movement of contaminants by wind or dissolved nutrients by water currents.

2.6.1.2 Heat Transfer

Heat transfer is the transport of thermal energy from a higher temperature zone to a lower temperature region. Conduction, convection, and radiation are the three primary heat transport methods

- **Conduction**-The transfer of heat within a solid substance or between objects in direct physical contact is referred to as conduction.
- **Convection**-Convection is the movement of a fluid (liquid or gas) that transfers heat. It happens as a result of density discrepancies induced by changes in temperature within the fluid.
- **Radiation**-Thermal radiation is released and absorbed by the droplet and the surrounding air. This radiation transmission can contribute to the overall heat exchange between the droplet and the air, especially when the temperature differences are significant.

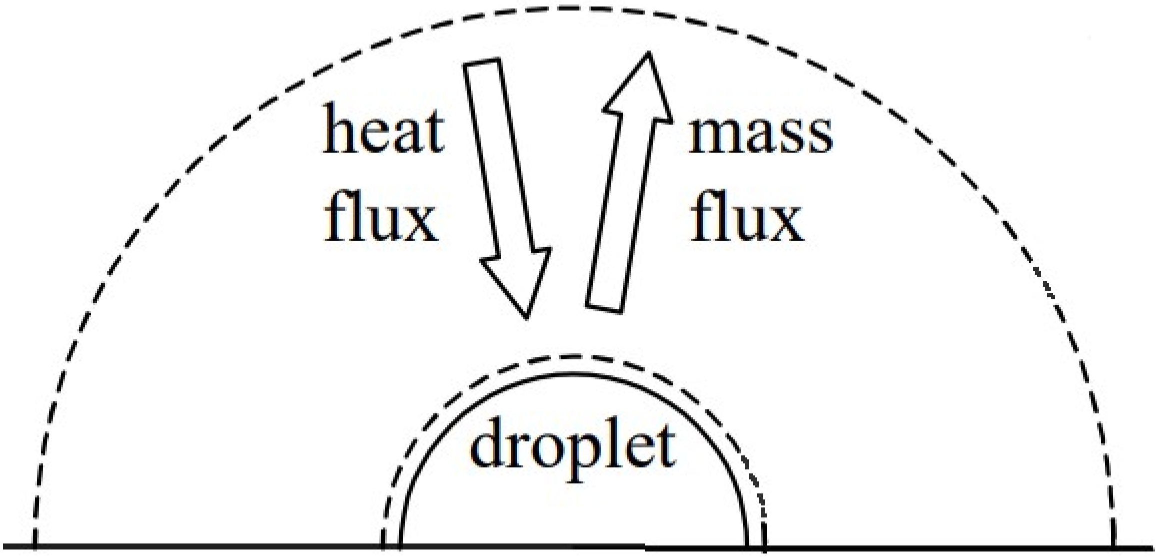

Figure 2.3: Evaporation of a single Droplet

2.7 Governing Equations

The evaporation of a droplet is a natural process in which a liquid droplet undergoes a phase change from vapor to liquid by losing mass and releasing heat.

2.7.1 Mass Flux

The rate of mass evaporation per unit area of the droplet surface.

$$\dot{m} = \rho \cdot A \cdot v \tag{2.1}$$

- $\dot{m}$ is the mass flux (kg/s).
- ρ is the density of the liquid (kg/m^3).
- A is the area of the droplet's surface (m^2).
- v is the evaporation velocity (m/s).

2.7.2 Heat Flux

The rate of heat transfer per unit area from the surface of a droplet.

$$Q = h \cdot A \cdot (T_{\text{droplet}} - T_{\text{surrounding}}) \tag{2.2}$$

- Q is the heat flux (W).
- h is the heat transfer coefficient $\left(\frac{W}{m^2 \cdot K}\right)$.
- A is the area of the droplet's surface (m^2).
- T_{droplet} is the temperature of the droplet's surface (K).
- $T_{\text{surrounding}}$ is the temperature of the surrounding environment (K).

2.7.3 Thermal Equilibrium

The rate of evaporation (mass flux) is equal to the rate of heat transfer (heat flux).

$$\rho \cdot v = h \cdot (T_{\text{droplet}} - T_{\text{surrounding}}) \tag{2.3}$$

This equation ensures that the droplet remains at a stable temperature during the evaporation process.

2.8 Factors Affecting Heat and Mass Transfer in a System with Uniform Temperature

In a system where the temperature is the same within a single droplet the limits of heat transfer and mass transfer depend on physical properties like,

1. **Thermal conductivity**-The thermal conductivity of the droplet medium will affect the rate of heat transfer.
2. **Mass Diffusivity**- The mass transfer is influenced by mass diffusivity. Lower diffusivity will result in lower heat transfer.
3. **Surface area and Volume**-The surface area of the droplets with respect to their volume plays a very significant role in heat and mass transfer. Smaller droplets with a larger surface area-to-volume ratio have higher transfer rates compared to larger droplets.
4. **Phase Change**-When the droplets undergo phase changes (evaporation or condensation), heat and mass transfer rates can be affected. Phase changes require latent heat, which can impact the overall transfer process.

5. **Thermodynamic Properties**-The specific heat capacity and density of the substances involved affect the amount of heat transferred.
6. **External Factors**- Factors like Temperature, Pressure, & velocity of the surrounding medium can influence heat and mass transfer rates.

2.9 Calculation Model

This section outlines the calculation model adopted for the analysis of droplet evaporation in the water-injected compressor system. The selection of the model is really important for calculating heat and mass transfer phenomena during droplet evaporation. To ensure a reliable approach, we thoroughly evaluated numerous existing models that have been proposed by the processes.

- **Model Evaluation Process** - The selection of the most suitable model from the literature study involved an evaluation process. I conducted a literature review to identify various droplet evaporation models, each designed to address specific aspects of a complex phenomenon. Evaluation criteria consider model precision, applicability to the water-injected compressor system, computational efficiency, and previous experimental validation.
- **Established Models**- I gave priority to established models in the field of droplet evaporation. The Meacock (2005) model is a well-established model in the research of droplet evaporation, and also previous applications are also taken into account. This well-established is sufficient to give us confidence in the model's capability to yield reliable results for our study.
- **Experimental Validation**-The experimental validation is available with an aspect in the domain of droplet evaporation. In previous studies, the Meacock (2005) model revealed good results with existing experimental data. This agreement provides additional support for our choice to use the Meacock model.
- **Comprehensive approach**-Having the complexities of droplet evaporation inside the water-injected compressor system, I wanted a model that could account for both heat and mass transfer. The Meacock (2005) model provides a comprehensive methodology that allows us to describe the interaction of these critical events.

- **Accessibility**-The Meacock (2005) model has very clear explanations and also eased its application. This allowed us to focus on studying the data rather than dealing with implementation issues.

2.10 Evaporative Analysis

A fundamental understanding of how liquid droplets interact with the free stream. Consequently, this section conducts a comprehensive review of the literature on droplet evaporation.

The exploration is structured into two parts: The first section focuses on stationary droplet evaporation, while the second section addresses the more intricate scenario involving evaporation with velocity slip at the interface between the droplets and the surrounding gas phase. But our Main focus is without Velocity slip where there is no interaction of air(Air is moving at the same speed as the Droplet moves).

2.10.1 Evaporative analysis without Velocity slip

The evaluation in this technique assumes no velocity slip effect, considering gas flow and liquid water flow as independent entities with no interactions between molecules on surfaces. This simplifies the analysis and may be more computationally easy. However, ignoring the velocity slip might result in less accurate forecasts, especially when the gas-liquid interaction has a considerable impact on the flow pattern. Meacock proposed a model which we are using here:-

1. **Mass Transfer**
2. **Heat Transfer**

2.10.2 Evaporative analysis with Velocity slip

The evaluation in this technique assumes velocity slip effects. The velocity slip effect at the gas-liquid interface is included in the study. It takes into account the interaction of the gas and liquid phases, simulating how gas and liquid water molecules interact and flow differently along the compressor surfaces.

1. **Mass and Heat Transfer**

2. **Momentum Transfer**

Chapter 3

Reference Model Analysis

For the analysis of the reference model, the Department of Mechanical Engineering at the University of Duisburg-Essen provided a program to understand how droplet evaporation could be modeled on the basis of the program. The program is based on the work of Barabas, 2012 model [10] which is explained in this chapter.

3.1 Introduction

The injection of water into gas turbines has been a subject of intensive research for decades due to its potential to significantly increase power and efficiency compared to the simple gas turbine cycle. One of the key areas of interest in this field is the evaporation of water droplets in the hot and humid conditions found in gas turbines.

To address this gap in understanding, the Department of Mechanical Engineering at the University of Duisburg-Essen developed a novel test facility. This facility enables the investigation of droplet evaporation in conditions that mimic the rear compressor stages of a gas turbine. The results obtained from this experimental setup are compared to the simulations of a 1D model for droplet evaporation. This chapter focuses on evaluating the agreement between the simulation results and the experimental data at elevated pressure and temperature levels.

3.2 Background

Gas turbines play a crucial role in various industrial applications, and improving their performance is a constant pursuit as defined in Chapter 2. However, wet compression introduces challenges as water droplets injected into the system remain in the flow. Understanding the behavior of these water droplets, particularly their evaporation, at high pressures and temperatures, such as those encountered in the first stages of the compressor, has been a topic of investigation. Previous numerical studies have provided insights into droplet evaporation at low pressures and temperatures, but little experimental data exists for the conditions found in rear compressor stages.

3.3 1D Evaporation Model

A 1D (One-Dimensional) evaporation model is a mathematical or computational model used to describe and predict the evaporation process in a single dimension. The model adopts a statistical approach to describe the distribution of the diameter of the droplets. It focuses on how a substance changes from a liquid phase to a vapor phase along a specific direction or coordinate, typically over time. This type of model simplifies the complex process of evaporation.

3.4 Basic Droplet Evaporation Model

The Abramzon and Sirignano [11] droplet evaporation model is a fundamental mathematical model used to describe and predict the evaporation process of a single liquid droplet suspended in a gas environment. This model provides insight into how a liquid droplet shrinks and eventually disappears as it evaporates into the surrounding gas. The model uses several assumptions:-

- The droplet is spherical and initially at rest
- Surrounding gas is at a constant temperature & pressure
- Liquid properties are constant
- No external forces acting on the droplet

3.4.1 Governing Equation

Basic equations used in this model include the conservation of mass. These equations are applied to describe how mass is transferred from the droplet to the gas phase.

3.4.1.1 Mass Transfer

The model is based on the principle of mass transfer, which describes the movement of mass (in this case, liquid molecules) from a region of higher concentration (inside the droplet) to a region of lower concentration (in the surrounding gas).

3.5 Evaporation rate

The rate at which the droplet evaporates is determined by the mass transfer process. The key parameter governing this rate is the **Sherwood number** (Sh), which relates the mass transfer rate to the physical properties of the droplet and the surrounding gas.

3.6 Experimental Analysis

A novel test facility was developed to investigate droplet evaporation at elevated pressure and temperature levels. Located at the Department of Mechanical Engineering at the University of Duisburg-Essen, this facility enables laser-based measurements of water nozzle sprays under conditions of high temperature (up to 673K) and high pressure (up to 1 MPa). The test facility includes several key components:

- An intercooled 4-stage-radial compressor to compress ambient air.
- An electric heater downstream of the compressor to raise the temperature of the main flow.
- A measuring section comprising a 1 meter long glass tube with a 102mm inner diameter.

- A water injection nozzle is placed at the beginning of the measurement section.
- A Phase Doppler Particle Analyzer (PDPA) system for optical access to measure spray patterns.
- A bypass system for adjusting the main flow velocity while maintaining constant temperature and pressure conditions.

3.6.1 Model Analysis

For the analysis of droplet evaporation, Barabas uses three models for the evaluation of droplet evaporation.

3.6.1.1 Model A-Basic Model

This model considers a spray of identical droplets that do not break down. These droplets are assumed to be perfect spheres with uniform temperatures and equal diameters. Each droplet is surrounded by a gas film to account for heat and mass exchange with the surrounding flow. The properties of the gas and water are based on the Kretzschmar Property Libraries.

$$\dot{m}_d = 2 \cdot \pi \cdot \rho_g \cdot D_d g \cdot r_d \cdot S_h \cdot ln(1 + B_M) \tag{3.1}$$

The key equation for this model is given by Equation (3.1), which describes the evaporation mass flow rate for a single droplet. It takes into account factors such as the droplet radius, the density of vapor in the gas film, and the diffusion rate between the droplet and the main flow. Equation 4.1.1 calculates the Spalding mass transfer number.

3.6.1.2 Model B - Parallel Calculations

Model B builds upon Model A by considering multiple droplet diameters simultaneously within each time step. Instead of assuming all droplets are identical, the Model starts with an initial droplet diameter distribution based on experimental data. In this model, it is still assumed that droplets do not influence each other, so the heat and mass transfer rates between each droplet size and the main flow are calculated independently. After a time step, the new main flow properties are averaged.

3.6.1.3 Model C - Droplet Breakup Model

Model C further extends the analysis by incorporating a droplet breakdown model. This model is based on the work of Schmehl et al[12]. with some simplifications. It considers only one of the three possible droplet breakup mechanisms. When a breakup occurs, only a single secondary droplet size is assumed to result from the breakup, and a portion (25%) of the broken-up droplets is considered to instantly evaporate. The model calculates the breakup per time step.

3.7 Program analysis

The program, provided by the Chair of Turbo-machinery at the University of Duisburg Essen, has been employed for the calculation of the Sauter mean diameter (μm) as a function of the distance traveled by the spray (meters), as depicted in Figure 3.1. This program has been utilized as a valuable tool within the framework of this study to assess droplet evaporation processes and gain a comprehensive understanding of the associated scenarios. Additionally, it has facilitated the exploration of various scenarios through deliberate manipulation of boundary conditions, pressure, and temperature settings.

The principal objective of this thesis is to develop a program for modeling droplet evaporation in humid gas environments, specifically focusing on the evolution of droplet diameter over time. To achieve this goal, the program, originally designed for calculating droplet properties as a function of distance, will be adapted. This adaptation aims to enable the calculation of the diameter of the drop as a function of time, allowing a deeper exploration of the temporal aspects of droplet evaporation. Importantly, these adaptations will be conducted while preserving the foundational principles of the original model. This development is expected to yield valuable insights into the dynamic behavior of droplets within humid gas environments and aligns closely with the central objective of this thesis.

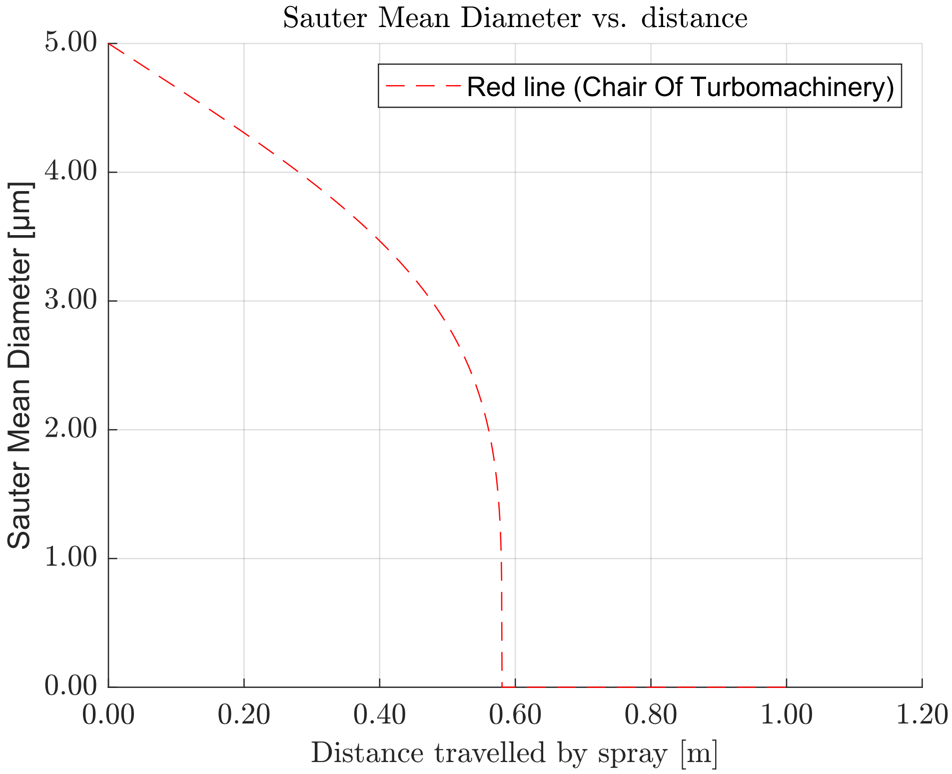

FIGURE 3.1: Satuer mean dia vs Distance traveled

3.8 Development of the Evaporation Model

3.8.1 Code Adaptation

In contrast to conventional analyses that primarily investigate the variation of Sauter mean diameter (SMD) with distance traveled by the spray, the primary emphasis of this study is to examine the temporal evolution of droplet diameter as a function of time within humid gas environments. While the original code was designed to calculate the SMD with respect to distance, our adaptation seeks to provide insights into the dynamic changes in the droplet diameter over time. This temporal approach is closely aligned with the central objective of this thesis, which is to explore the intricate time-dependent processes of droplet evaporation under specified environmental conditions.

Figure 3.2 illustrates the modular structure of the provided code for droplet evaporation modeling. The code comprises four distinct subfunctions, each serving a specific purpose in the overall simulation process.

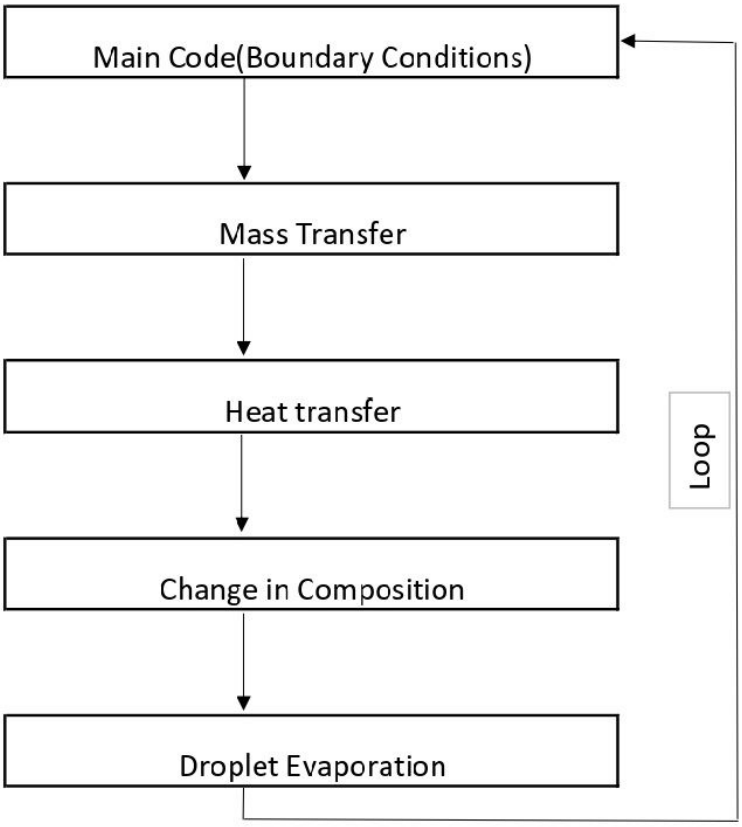

FIGURE 3.2: 1D Evaporation program approach

- Mass Transfer: This subfunction is responsible for calculating mass transfer rates between the droplet and the surrounding gas, considering factors such as concentration gradients and diffusion.

- Heat Transfer: The heat transfer subfunction handles the computation of heat transfer rates, accounting for temperature differences and thermal properties of the droplet and the gas.

- Change in Composition: This component addresses changes in droplet composition over time, taking into account chemical reactions or phase changes that may occur during evaporation.

- Droplet evaporation: The core of the code, this sub-function integrates the results from the mass transfer, heat transfer, and composition change calculations to model the evaporation process itself.

Additionally, the figure shows the presence of the main function, which arranges the flow of data and controls the execution of these sub-functions. Together, these elements collectively enable the simulation of droplet diameter evolution over time.

In the pursuit of developing an evaporation model to compute droplet diameter as a function of time, it became evident that certain crucial modifications were imperative to the existing functions and boundary conditions. While the pre-existing functions provided a solid foundation for our work in modeling droplet evaporation, they primarily focused on distance-dependent properties. To transition our model into a time-dependent framework, we recognized the need to reconfigure and augment these functions. This involved a re-assessment of the boundary conditions governing the droplet-gas interactions and the development of a new function tailored to capture the intricate temporal dynamics of droplet evaporation. These adaptations were essential to ensure the model's capability to simulate the evolution of droplet diameter over time, a fundamental objective of this study.

The boundary conditions applied in the experiments are presented in Table 3.1, including the main flow temperature, the main flow pressure, the average main flow velocity, the water temperature and the fraction of mass of the injected water. After defining the parameters, the analysis I obtained is shown in Figure 3.3.

Parameter	**Values**
Main Flow Temperature (K)	298.05
Main Flow Pressure (Bar)	0.98
Average Main Flow Velocity (m/s)	1
Droplet Temperature(K)	282.26
Injected Water Mass flow rate (kg/sec)	0.01
Air Mass flow rate (kg/sec)	100

Table 3.1: Boundary conditions

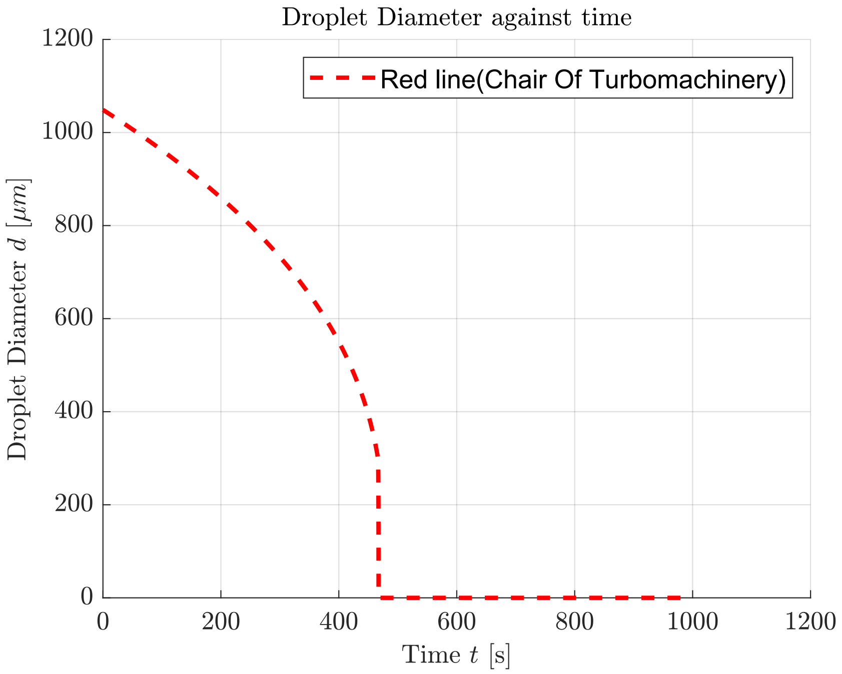

FIGURE 3.3: Droplet Diameter vs time

Chapter 4

Vapourisation of a droplet

4.1 Evaporation model

The approach described in this statement is inspired by the work of Meakok (2005) [13], which uses a similar notation. However, it is specifically applicable to flows without velocity slips. In this context, the flow within the compressor is assumed to be a combination of dry air and water vapor from liquid droplets. These droplets are spaced apart enough to avoid interference with each other. The term ”mixture” encompasses all the components mentioned, including dry air, water vapor, and liquid droplets. The ”gaseous phase” refers only to dry air and water vapor, excluding liquid droplets.

Based on Meacock’s theory, the equations for droplet evaporation can be summarized as follows: Assumptions:-

1. Spherical Droplets
2. Wall Interaction is neglected
3. Droplet breakup is neglected
4. Monodisperse spray
5. Steady-State conditions

4.1.1 Mass Transfer

The mass flow relative to a stationary evaporating droplet consists of two phenomena: the first represents the diffusive mass flow driven by the vapor concentration gradient described by Fick's law, and the second is due to the fact that air does not dissolve in the droplet, resulting in a net flow of mass away from the droplet itself.

Considering that the total mass flow is related only to the vapor mass flow since the air does not diffuse into the droplet, We can write:

$$J = J_a + J_v = J_v = x_v J - \rho D_v \frac{\delta x_v}{\delta r} \tag{4.1}$$

Here, D_v is the constant diffusion coefficient, and x_v is the fraction of mass of the vapor.

Under quasi-stationary conditions, the vapor mass flow can be considered independent of the radius, resulting in:

$$J_{0r0}^2 = J_r^2 = x_v J_{0r0}^2 - \rho D_v \frac{\delta x_v}{\delta r} r^2 \tag{4.2}$$

Here, J_0 is the mass flow relative to droplets of initial diameter r_0.

Integrating the equation between the surface of the droplet and infinity, we obtain the following.

$$J_0 = \frac{\rho D_v}{r_0} \ln \left[\frac{1 - x_{v\infty}}{1 - x_{v0}} \right] \tag{4.3}$$

Here, $x_{v\infty}$ and x_{v0} are the mass fractions in the free stream and on the droplet surface, respectively.

$$X_{v0} = \frac{ps}{s} \tag{4.4}$$

The mass fraction X_{v0} can be calculated by evaluating the vapor mole fraction as the ratio between the saturation pressure (evaluated at the droplet surface temperature) and the free stream pressure. Then, we have:

$$x_{v0} = \frac{x_{v0}}{x_{v0} + (1 - x_{v0})\frac{M_g}{M_v}} \tag{4.5}$$

Here, M_g and M_v are the molar weights of air and vapor, respectively.

The droplet growth rate can then be deduced from the vapor mass flux rate;

$$\frac{Dr_0}{Dt} = -\frac{J_0}{\rho_L} = -\frac{\rho D_v}{\rho_{Lro}} ln\left(1 + BM\right) \tag{4.6}$$

where ρ_L is the liquid density and BM is Spalding's mass transfer number.

Finally, by introducing the following:

$$B_M = \frac{x_{v0} - x_{v\infty}}{1 - x_{v0}} \tag{4.7}$$

4.1.2 Heat transfer

The heat and mass transfer processes are strongly coupled, and it is necessary to evaluate the heat flux in order to determine the droplet temperature, and hence the vapor mass fraction at the droplet surface.

In the Meacock thesis, the governing equation of heat transfer for droplets is derived on the basis of the quasi-steady heat- and mass-transfer assumptions.

The heat flux (Q_0) is determined using Spalding's analysis and is given by:

$$Q_0 = \frac{cp_v \cdot J_0 \cdot (T_\infty - T_0)}{1 - \exp\left(\frac{cpv \cdot J_0 \cdot r_0}{\lambda}\right)} \tag{4.8}$$

where cp_v is the specific heat capacity of the vapor, J_0 is the convective heat transfer coefficient, T_{ref} is a reference temperature close to the wet-bulb value, r is the droplet radius and λ is the thermal conductivity of the air.

Spalding Heat transfer number B_T which is defined as,

$$B_T = \frac{J_0 \cdot c_{p_v}(T_\infty - T_0)}{Q_o} \tag{4.9}$$

where:

B_T : Spalding Heat transfer number,

J_0 : mass flux,

c_{p_v} : specific heat capacity of the vapor,

T_∞ : temperature of the surrounding environment (infinity) or bulk temperature,

T_0 : initial temperature of the droplet,

Q_o : heat of vaporization or condensation per unit mass of liquid (latent heat).

To overcome mathematical stiffness in numerical integration, a semi-analytical technique is used. By linearizing the expressions for Q and J with respect to a small perturbation in T, the equation can be expressed as:

$$\frac{dT_o}{dt} = \frac{3}{CP_l \cdot rho_l \cdot r_o} \cdot (Q_o + J_0 \cdot L) \tag{4.10}$$

where t_t is the droplet temperature relaxation time.

This simplified equation can be integrated analytically, giving:

$$\frac{dT_o}{dt} = \frac{3 \cdot \rho \cdot D_v \cdot ln(1 + B_M)}{\rho_L \cdot cp_l \cdot r_0^2} \left[\frac{cp_v(T_\infty - T_0)}{(1 + B_M)^\alpha - 1} - L \right] \tag{4.11}$$

where T_0 is the initial droplet temperature and D_v is the diffusion coefficient of the vapor.

4.2 Constant property Model

4.2.1 Introduction

This chapter presents the heat and mass transfer model we have adopted to investigate the evaporation of a droplet in humid gas. The ”constant property model,” as we call it, serves as a core framework for understanding the complex interactions between droplets and humid gas throughout the evaporation process in a simplified way.

4.2.2 Model overview

The constant property model is designed to provide a simplified representation of the droplet evaporation process. Unlike more complex models, this approach focuses on Meacock algebraic equations of heat and mass transfer that offer a balance between accuracy and computational efficiency, making it particularly well-suited for scenarios where rapid assessments are essential.

4.2.3 Suitability of the Model for Droplet Evaporation in Humid Gas

The Model is suitable for the following points:-

1. Model Assumptions-The model assumptions I have chosen in the constant properties model account for humidity, which is a critical factor influencing droplet evaporation. The presence of humidity significantly impacts the mass and heat transfer rates between the droplet and the surrounding gas.
2. Mass and heat transfer coupling- This phenomenon occurs during droplet evaporation in a humid gas. It enables a more comprehensive understanding of the dynamic behavior of droplets and how they interact with the surrounding gas environment.
3. Validations with experimental results-It provides a valuable tool for interpreting or predicting experimental results.
4. Applicability to Engineering Scenarios-It is suitable for practical applications in industries where droplet evaporation plays a significant role, including fuel droplet combustion in internal combustion engines, spray cooling in power generation, etc.

4.2.4 Boundary Conditions

The boundary conditions in the constant property model are critical to characterizing the interactions between the droplet and the surrounding humid gas. Specific conditions are taken from Ranz & Marshall [7], and Meacock's [13] work, which is important for establishing the interface between the droplet and the gas in order to adequately describe the transfer of mass. Boundary conditions such as inlet pressure, Droplet temperature, the diameter or radius of a droplet, surrounding temperature, and mass flow rate of air in which many of them are based on the experimental analysis from Ranz and Marshall[7]. The constant property model is dependent on mass transfer based on Fuller, Schettler, and Giddings (1966)[14] from eq 4.14 diffusion correlation because the pressure is below 20 atmospheric.

Table 4.1: Basic conditions for determination of constant property model

Property	Value
Air Velocity(constant)	1 m/s^{-1}
Pressuse	0.98 Bar
Dia of Droplet	1048.8 μm
Ambient Temperature	24.9°C
Droplet Temperature	9.11°C
Mass flow rate (Air)	100kg/s
Mass flow rate(Vapor)	0 kg/s

4.2.5 Role of Fluid Properties

Fluid properties play a critical role in the process of droplet evaporation in humid air. These properties influence how the droplet interacts with the surrounding humidity, or the presence of water vapor in the surrounding gas, which significantly affects the evaporation process Here are some key fluid properties and their roles:

- **Saturation pressure**: Saturation pressure represents the maximum vapor pressure of water that can exist at a given temperature. it's a key parameter because it determines the driving force for evaporation. In humid air, the saturation pressure is influenced by the temperature. A higher temperature increases the saturation pressure, creating a greater vapor pressure gradient at the droplet's surface. This, in turn, promotes faster evaporation.
- **Partial Pressure of Water Vapor**: The partial pressure of water vapor is the pressure exerted by the water vapor in the gas mixture. It's directly related to the humidity of the surrounding air. In humid air, if the partial pressure of water vapor is higher. This affects the concentration gradient of water vapor between the droplet's surface and the surrounding air. The

greater the difference, the faster water molecules will diffuse away from the droplet's surface, accelerating evaporation.

- **Diffusivity**: Diffusivity is a measure of how quickly water vapor molecules may flow through a gas. It is required for the passage of water vapor away from the surface of the droplet. Diffusivity can be affected by increased humidity. Although water vapor diffusivity in the air does not change greatly with humidity, it is critical for forcing water vapor transportation away from the droplet's surface, especially in humid environments.

- **Vapor Concentration gradient**: The rate of vaporization is determined by the concentration difference of water vapor between the droplet's surface and the surrounding air. In humid air, the vapor concentration gradient is initially high because of the elevated partial pressure of the water vapor. This gradient initially drives rapid evaporation. However, as the droplet shrinks and the surrounding air becomes more saturated with water vapor, the gradient decreases, slowing down evaporation.

- **Heat transfer**: The fluid properties, such as thermal conductivity and specific heat capacity, determine how efficiently heat is transferred between the droplet and the surrounding air. The latent heat of vaporization (the amount of heat required to evaporate water) is important in humid air. The air's heat transmission qualities influence how efficiently this latent heat is transmitted to the droplet, affecting its temperature and, as a result, its evaporation rate.

- **Temperature**: It can influence the saturation pressure and the molecular interaction in the gas. In humid air, higher temperatures can significantly increase saturation pressure. This effect, coupled with the increased molecular motion, leads to a more vapor pressure gradient at the droplet's surface, promoting faster evaporation.

- **Humidity and Relative Humidity**: Humidity measures the actual water vapor content in the air, while relative humidity compares this content to the maximum possible at a given temperature. High humidity or high relative humidity reduces the vapor pressure gradient at the droplet surface, slowing down evaporation. Lower humidity or lower relative humidity, on the other hand, increases the vapor pressure gradient and accelerates evaporation.

4.2.5.1 LibHuAir_Xiw

To facilitate our analysis and calculations, we utilize the library `LibHuAir_Xiw`. This library plays a crucial role in enabling accurate modeling and simulation of droplet evaporation in humid air.

`LibHuAir_Xiw` provides a comprehensive set of tools and functions for handling [specific tasks the library helps with, such as heat and mass transfer calculations in humid environments, thermodynamic properties determination, etc.]. By leveraging the capabilities of this library, we aim to enhance the precision and reliability of our research outcomes.

The integration of `LibHuAir_Xiw` into our calculations is a pivotal step towards achieving our objectives.

4.2.6 Evaporation of a droplet

As mentioned above, the study of the evaporation of single droplets can serve as a valuable foundation for understanding the overall droplet evaporation process. The evaporation of a droplet is a fundamental process that occurs when a liquid droplet is exposed to a gas environment. The difference in the pressure of the vapor immediately above the surface of a droplet and the ambient (partial) pressure of the vapor far from the drop drive a diffusive flux that leads to a gradual decrease in the volume of the liquid, which is termed droplet evaporation[15]. This process is important in a variety of scientific, industrial, and natural contexts, which affect sectors such as engineering, meteorology, and medicine. In this part, we discuss droplet evaporation and how the constant-property model may help us understand this difficult process in a simplified way. The vapor pressure at the droplet surface controls the passage of molecules from the liquid phase to the gas phase as the droplet is exposed to the gas environment. This molecular migration is the mass transfer process, in which water molecules at the droplet surface change to vapor form in the gas (air) that is represented with a dotted circle; see Fig.4.1. Young (1995)[16] provides a good theoretical background of gas-droplet flows with phase change, nucleation, and velocity slip which is restricted to non-nucleating flows without velocity. Since velocity slip is neglected, the mass fraction of air and the number of droplets in each group (provided they do not completely evaporate) remain constant, where n_i is the number of droplets per unit mass of water and

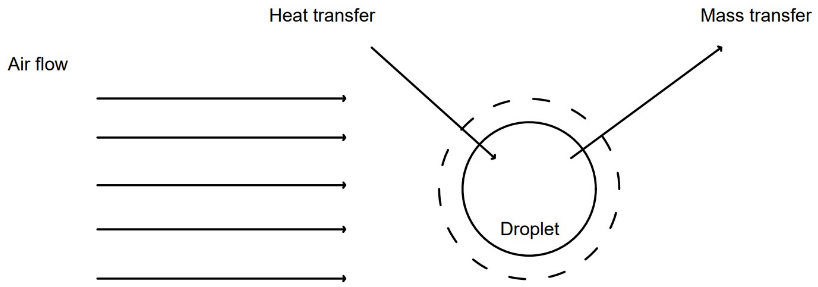

FIGURE 4.1: Evaporation of a droplet

D/D_t is the derivative with respect to time following the flow (and hence the droplet) and the subscript i denotes a droplet.

$$\frac{dn_i}{dt} = 0 \tag{4.12}$$

4.2.7 Vaporization and diffusion

The process of vaporization starts on the surface of a droplet, where water molecules gain sufficient energy to transition from the liquid state to the gaseous state. This energy transfer occurs due to the contrast in vapor pressure between the surface of the droplet and the neighboring gas which is air. As molecules escape from the droplet, their size decreases over time as seen in fig 4.2. This size reduction is a characteristic commonly seen during the evaporation of a droplet, which is based on 4.1.1

Moreover, water vapor diffusion inside the gas phase is also critical. The vapor concentration gradient causes vapor molecules to diffuse from higher concentration regions (near the droplet) to lower concentration regions (far away from the droplet). This diffusion mechanism contributes to the continual supply of vapor molecules at the droplet's surface, allowing for long-term evaporation shown in eq 4.14. By continually replenishing the vapor molecules at the droplet's interface, diffusion enables a sustained and controlled evaporation rate over time. This dynamic equilibrium between vapor molecules diffusing outward and those being replenished from the liquid phase is crucial in understanding the intricacies of droplet evaporation.

From Eq. 4.6 we can find how the droplet evaporates over time.

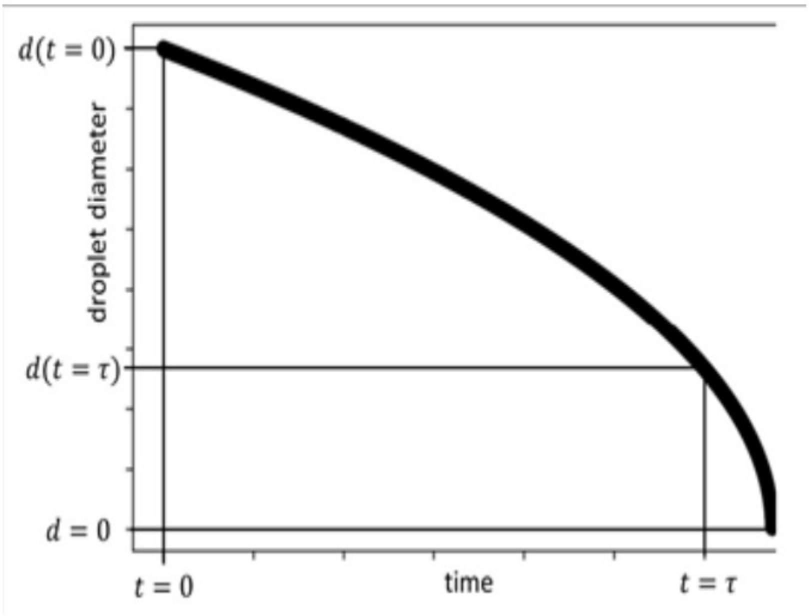

FIGURE 4.2: diameter vs time

4.2.8 Energy Exchange

Heat transfer is intrinsically related to evaporation. Energy is necessary to overcome the intermolecular interactions that hold the liquid together as molecules shift from the liquid phase to the gas phase. As a droplet undergoes evaporation, water molecules at the droplet's surface gain sufficient energy from their surroundings to overcome the attractive forces that keep them in the liquid phase. This energy requirement, known as the latent heat of vaporization, is absorbed from the surroundings, resulting in a reduction in temperature.[17] As a result, the temperature of the droplet falls as it evaporates. As the evaporation progresses, the combined effects of mass transfer and heat transfer shape the droplet's behavior. the droplet loses both mass and thermal energy to the vapor phase. This not only leads to a decrease in the droplet's size but also a decrease in its temperature over time refer to fig 4.2.

4.2.9 Evaluating the model

The droplet radius is one of the main factors that influence the performance of the evaporation of the droplets[18]. It is very difficult to choose the radius of the droplets because it is a key parameter in the model. Taking into account previous studies and experimental results, the model defines the diameter and radius according to it which is 0.011 cm which is nothing but 1048.8 μm in diameter and half its radius. Spalding [19] gives the correlation that the square of the droplet diameter decreases linearly with time which is also proportional to the droplet radius. This assumption fits well for droplets in resting air at ambient conditions which are described above Tab. 4.1. For evaluating the model, the Spalding mass transfer number $_{B_M}$ is used, which is an indicator of the mass transfer between the droplet and the surrounding gas.

$$B_M = \frac{x_{v0} - x_{v\infty}}{1 - x_{v0}} \tag{4.13}$$

These calculations proposed in the constant property model, which are considered, are based on the parameters according to their boundary conditions. This model is used to evaluate how the droplet evaporates over time. Here, It is assumed that there is no velocity slip between the droplets and the gaseous phase. To evaluate the model, we first evaluate the diffusion rate within the droplet, also explained in sec.4.2.4.By this parameter, we evaluate that the diffusion coefficient

$$D_{AB} = \frac{(10^{-7}) \cdot (T)^{1.75}}{p_{in}((\Sigma V_A^{1/3}) + (\Sigma V_B^{1/3}))^2} \cdot \sqrt{\left(\left(\frac{1}{\text{MolarWeight\_water}}\right) + \left(\frac{1}{\text{MolarWeight\_air}}\right)\right)} \tag{4.14}$$

where:

D_{AB} : Diffusion coefficient of vapor in air

p_{in} : Pressure inlet

T : Ref temperature

This diffusion coefficient used by Fuller, Schettler, and Giddings, which is a more complex and comprehensive model for describing diffusion, particularly in the context of multi component mixtures and porous media, while another diffusion model which is used by Meacock in their work is Flick's law of diffusion which is limited to only a single substance in a homogeneous medium.

After getting all the above parameters we calculate the droplet growth rate which is deduced from mass flux rate J_0 from eq 4.6.

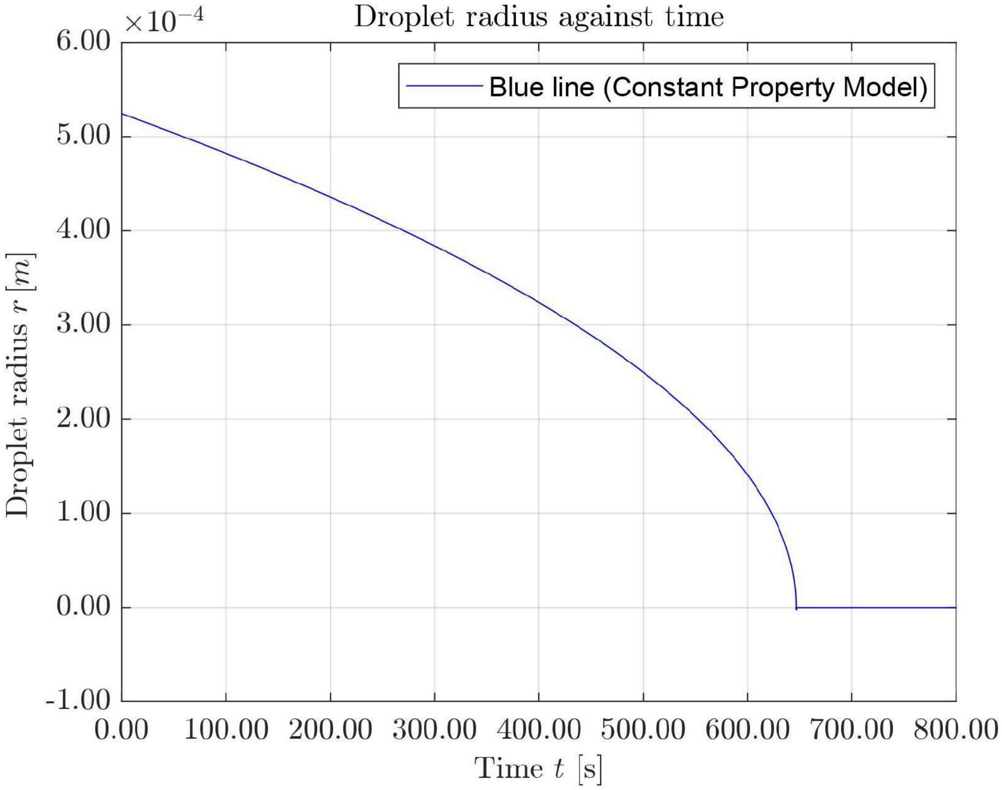

FIGURE 4.3: Evaporation of a droplet

$$\frac{Dr_0}{Dt} = -\frac{J_0}{\rho_L} = -\frac{\rho D_v}{\rho_{Lro}} \ln\left(1 + BM\right)$$

From the graph 4.3, you can see that the radius of the droplets decreases with time and evaporates completely.

4.2.10 Validation of a constant property model

In an influential study, Ranz and Marshall (1952) conducted experimental research on the evaporation of a liquid droplet suspended in still air. They used a glass capillary to suspend the droplet and positioned a 0.5mm thermocouple at its center to monitor the temperature changes during the evaporation process. The model is based on the parameters used by Ranz in their research. The droplet is found to be fully evaporating before 800 s from experimental studies, which we used as a constant parameter for the evaporation time. To validate the constant property model with the experimental graph obtained by Ranz shown in fig 2.2 we convert the linear graph to a Route graph(nonlinear graph) meaning from the Square of droplet diameter we convert to diameter(D^2 to D) for comparing the result with

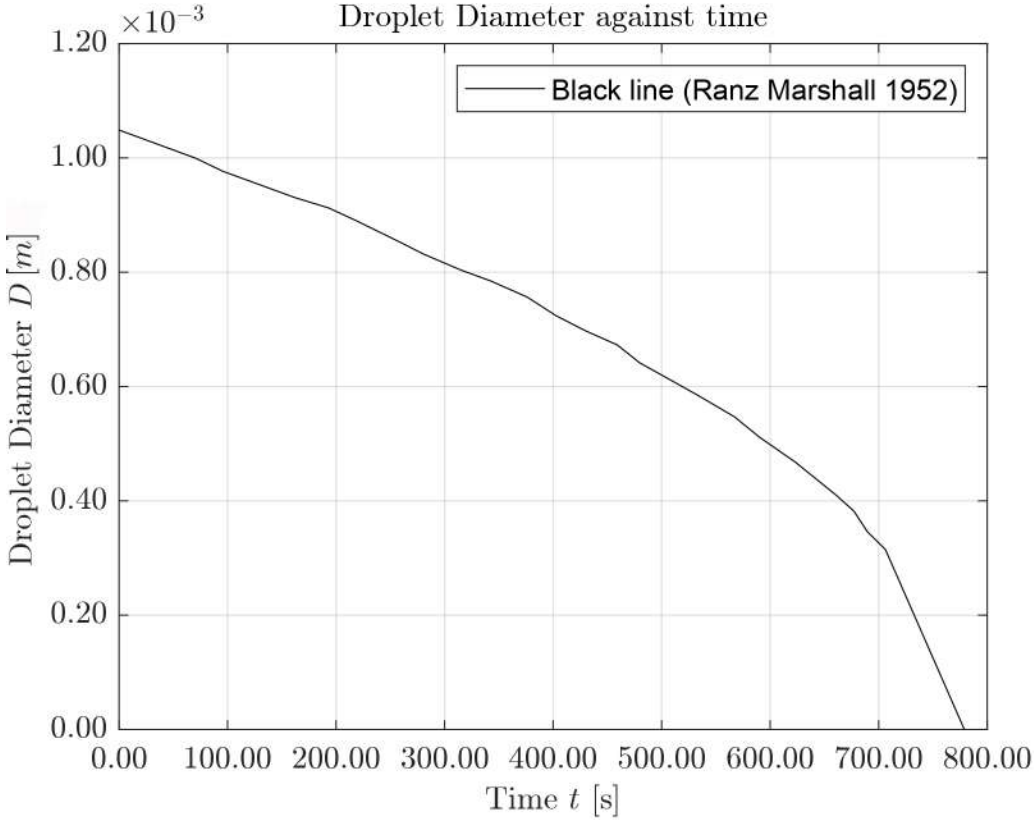

FIGURE 4.4: Initial Droplet Diameter is 1048.8 μm

the code we obtained in Matlab. After Converting the graph and comparing it with the Ranz graph analyzing the simulation the constant property model graph evaporates as same as the Ranz experimental study graph means the decreasing curvature of the Ranz graph is as same as the constant property graph. as shown in fig 4.5.

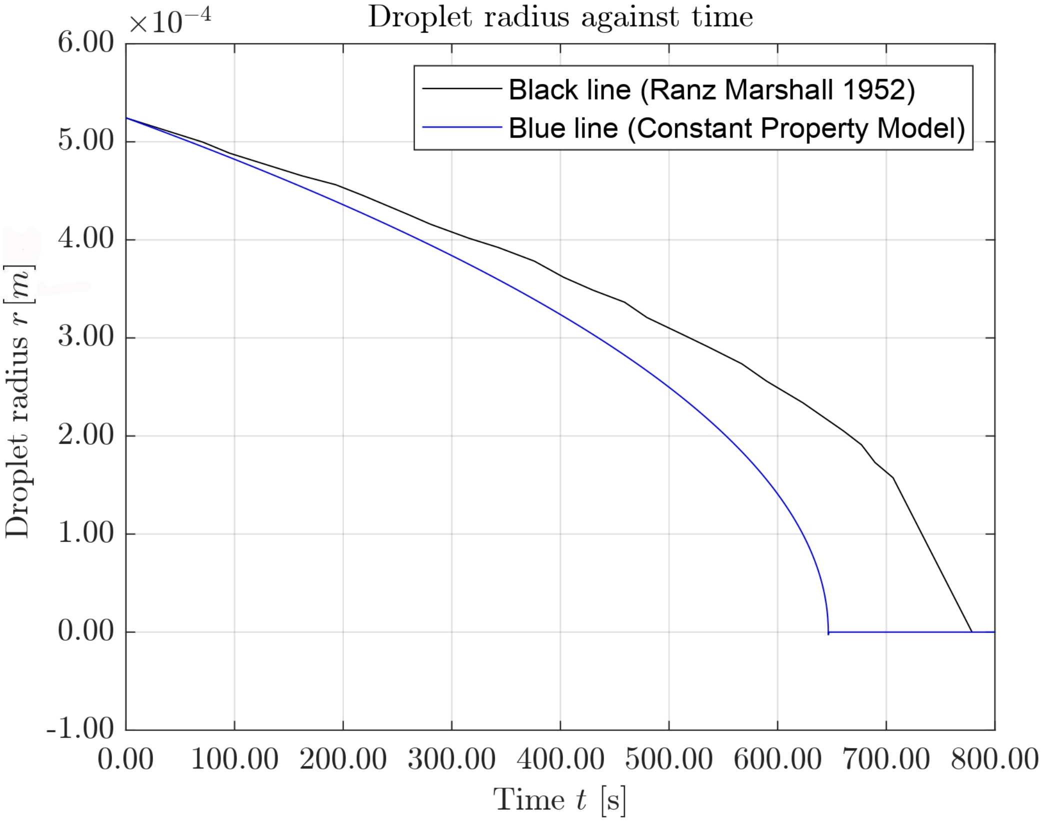

Figure 4.5: Comparison of Droplet radius vs time

Chapter 5

Analysis of Result

In the preceding sections, the model is discussed in detail and the mechanism of droplet evaporation, with the implementation of the LibHuAir Xiw library for our model analysis. The library's integral role to provide significant data in our simulations, particularly in the accurate modeling of heat and mass transfer processes in humid air conditions.

The evaporation of a droplet, as a fundamental process, was observed to follow the theoretical predictions. The experimental data confirms with the simulations, showing a gradual decrease in droplet radius over time. This volume reduction is consistent with the mass transfer process, where water molecules transition from the liquid phase at the droplet surface to the vapor phase in the surrounding air.

Figure 4.2 express the relationship between droplet diameter and time, where a clear inverse correlation was evident. The constant-property model simplified the complex interactions involved in droplet evaporation, allowing us to derive a significant understanding of the process. The validation of the model came through the close alignment of our simulated data with that of Ranz and Marshall's experimental findings from 1952.

The graph depicted in Figure 4.3 illustrates a consistent decrease in droplet radius over time, affirming the theoretical solid foundation that suggest a square relationship between droplet diameter and evaporation time. This relationship was further substantiated by the droplet growth rate equations, which showed a decrease in droplet radius proportional to the logarithm of the sum of the Spalding mass transfer number.

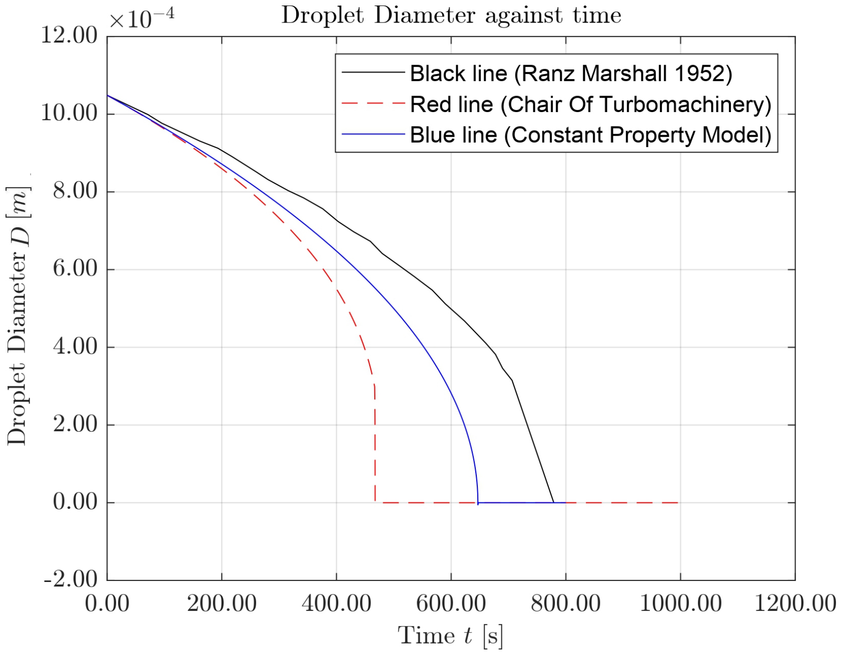

FIGURE 5.1: Comparison of the results

The modelling of droplet Evaporation in humid gas using the constant property model is accurate as compared to the code given by the chair of turbo machinery 5.1.

In conclusion, the constant property model offers a valuable tool for studying droplet evaporation in humid gas environments, providing insights into the dynamic interactions between droplets and their surroundings.

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