UNIVERSITI PUTRA MALAYSIA

EXPERIMENTAL AND NUMERICAL EVALUATION OF NAPIER GRASS GASIFICATION IN AN AUTO-THERMAL FLUIDIZED BED REACTOR

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By

RAMIN KHEZRI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2018

DEDICATION

This study is wholeheartedly dedicated to my beloved parents, who have been my source of inspiration and gave me strength when I thought of giving up, who continually provide their moral, spiritual, emotional, and financial support.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman: Assoc. Prof. Wan Azlina bt. Wan Abdul Karim Ghani, PhD
Faculty: Engineering

Biomass gasification is a promising renewable energy generation technology as alternative to fossil based fuels for cleaner and sustainable future. At site auto-thermal gasifier built in affordable economic scale can overcome the high costs of grid lining, supplementary resources and the delivery of feedstock as main target for this study. A biomass gasification system with Napier grass as feedstock was investigated with the target of the producer gas to be used in direct combustion for power generation. The study consists of two main parts of experimental evaluations and numerical models. Experiments carried out to study the effect of three different operating parameters namely, temperature, equivalence ratio (ER) and static bed height (SBH) on the gasification of Napier grass in an auto-thermal bubbling fluidized bed gasifier. The results showed that the temperature has the most significant effect on the production of syngas as well as the composition of combustible species. The highest yield of syngas, with highest compositions of hydrogen and carbon monoxide and lowest yield of residues (i.e. biochar, tar and ash) were achieved at maximum temperature of 824°C. ER on the other hand has more complex effects on responses. The increase in ER up to 0.33 favored the yields of syngas, H_2 and CO however the inverse effect was observed for ER above 0.33. SBH was found an important factor to effect on the production of H_2 and CO and the maximum yields of each obtained at temperature of 824°C, ER of 0.33 and SBH of 0.105m. Common challenges encountered in performing the experiments were related to the complexity and instability of the process and the difficulties to maintain the temperature at a constant level due to the auto-thermal characteristics. Difficulties are expected to be diminished once achieved a steady-state operating condition through process improvement and optimization to which the process become adaptable to any imposed variations such as different feedstock types.

An integrated numerical simulation were developed to study over hydrodynamics and thermodynamics of the gasification process. Hydrodynamics of solid particles fluidization were modelled to study on the effect of superficial velocity, viscous and drag models on the expansion of fluidizing bed, formation and distribution of bubbles inside the gasifier. The effect of air distributor plate with different pore diameters was modelled individually to determine the initial condition of the fluid as entered the gasifier. The results showed that the turbulent model of RNG K-Ɛ describes the actual process more accurately than other fluid regimes. Laminar and turbulent models although resulted in similar bed expansion level, the turbulent model showed higher distribution of solid particles and their related interactions as the result. Thermodynamic studies were conducted to simulate the heat distribution and to determine the temperature profile of the reactor at any time step of the operation. The temperature values at steady operation were verified by experimental records. The conduction heat transfer from gasifier media into the center of a single particles with different diameters were studied individually to calculate the particle degradation period. It was found from the results that fully degradation of a particle to solid biochar as entered the gasifier at constant temperature takes place after 0.66, 1.1 and 1.55 seconds for particles with 300,500 and 700 μm diameters respectively. The effect of particle size and initial reactor temperature on heat distribution were evaluated as well. Using the model eases the monitoring of system behavior while functions under various operating conditions.

The findings from empirical optimization while integrated with numerical models provides an in-depth understanding over the gasification process and facilitates the scale-up determinations so that the technology in the future can be utilized in larger scales to provide power from biomass particularly in form of electricity in rural area.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGGEGASAN RUMPUT NAPPIER DI DALAM PENGGEGAS AUTO-TERMAL TERBENDALIR

Oleh

RAMIN KHEZRI

Mei 2018

Pengerusi: Prof. Madya Wan Azlina bt. Wan Abdul Karim Ghani, PhD
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Pengegasan biomass adalah teknologi penjanaan tenaga boleh diperbaharui yang berpotensi sebagai kepada tenaga daripada bahan api berasaskan fosil untuk masa depan yang lebih bersih dan mampan. Penggegas auto-termal yang dibina dalam skala ekonomi berpatutan dapat mengatasi kos sambungan grid yang tinggi, sumber tambahan dan penghantaran bahan bakar adalah sasaran utama kajian ini. Kajian yang dicadangkan untuk menilai sistem pengegasan sisa menggunakan rumput Napier sebagai bahan bakar bagi menghasilkan sintesis gas yang kemudiannya dapat digunakan dalam pembakaran langsung untuk penjanaan tenaga. Kajian ini terdiri daripada dua bahagian utama kajian eksperimen dan kaedah simulasi berangka. Bahagian pertama kajian, eksperimen dijalankan untuk mengkaji kesan tiga parameter operasi yang berbeza iaitu suhu, nisbah kesetaraan (ER) dan ketinggian statik ruang terbendalir (SBH) pada pengegasan rumput Napier di dalam pengegagas terbendalir. Reaktor yang dignnakan ber geometri silinder dengan ketinggian 1 m dan diameter 0.106 m dan dilengkapi dengan sistem penyejukan dan pembersihan. Pemilihan rumput Napier sebagai bahan mentah adalah kerana kelebihannya keupayaan hasil tuaian yang tinggi, pertumbuhan yang cepat dan nilai kalori yang tinggi (sekitar 17 MJ / kg). Secara ringkas, kajian menunjukkan bahawa suhu mempunyai kesan yang paling ketara terhadap pengeluaran sintesis gas serta komposisi spesis mudah terbakar seperti hidrogen dan karbon monoksida. Hasil tertinggi sinthesis gas, H_2, CO dan hasil lebihan terendah seperti bio-arang, tar dan abu dicapai pada suhu maksimum 824 ° C. ER sebaliknya mempunyai kesan yang lebih kompleks terhadap tindak balas. Peningkatan ER sehingga 0.33 cenderung menghasilkan sintesis gas, H_2 dan CO namun kesan songsang diperhatikan untuk ER melebihi 0.33. SBH pula didapati faktor kurang penting untuk menghasilkan pengeluaran H_2 dan CO di mana hasil maksimum masing-masing pada suhu 824 ° C, ER 0.33 dan SBH 0.105 m. Antara cabaran yang

sering dihadapi dalam menjalankan eksperimen adalah berkaitan dengan kerumitan dan ketidakstabilan proses dan kesukaran untuk mengekalkan suhu pada tahap yang berterusan. Kesukaran dijangka akan berkurang setelah mencapai keadaan operasi mantap melalui peningkatan kecekapan proses dan pengoptimalan yang prosesnya dapat disesuaikan dengan variasi yang dikenakan.

Oleh itu, simulasi berangka telah dibangunkan untuk mengkaji sifat hidrodinamik dan termodinamik proses pengegasan. Hidrodinamik zarah pepejal terbendalir dimodelkan untuk mengkaji kesan halaju superficial rejim ter bendalir yang berbeza dan pada pengembangan katil terbendalir dan pembentukan dan pengedaran gelembung di dalam penggegas. Kesan pengedaran udara dimodelkan secara individu untuk menentukan keadaan awal bendalir masuk seperti masukan penggegas. Hasilnya menunjukkan bahawa model bergelora RNG K-Ɛ menerangkan proses sebenar dengan lebih tepat berbanding rejim bendalir yang lain. Model laminar dan bergelora walaupun mengakibatkan pengembangan katil yang sama, pengagihan zarah pepejal dan interaksi mereka lebih tinggi dalam model bergolak. Kajian termodinamik telah dijalankan untuk mensimulasikan pengagihan haba dan menentukan profil suhu reaktor pada setiap langkah operasi. Nilai suhu kemudiannya divalidas oleh rekod percubaan. Penyebaran haba dari media penggegas ke dalam zarah tunggal telah dikaji secara individu untuk mengira tempoh pengerakan tunin zarah. Didapati bahawal bahawa zarah telah di transformasi sepenuhnya kepada bio-arang pepejal selepas 1.1 saat memasuki gasifier pada suhu malar. Penggunaan model ini memudahkan pemantauan tingkah laku sistem manakala fungsi di bawah pelbagai keadaan operasi.

Penemuan dari pengoptimuman empirikal semasa gabangar dengan model berangka memberikan pemahaman mendalam mengenai proses dan memudahkan penentuan skala sehingga teknologi di masa depan dapat digunakan dalam skala yang lebih besar untuk penjanaan kuasa dari biomass khususnya dalam bentuk elektrik di kawasan luar bandar .

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I certify that a Thesis Examination Committee has met on 31 May 2018 to conduct the final examination of Ramin Khezri on his thesis entitled "Experimental and Numerical Evaluation of Napier Grass Gasification in an Auto-Thermal Fluidized Bed Reactor" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AFR	Air to Fuel ratio
CCE	Carbon Conversion efficiency
CCD	Central Composite design
CGE	Cold gas efficiency
CV	Colorific value
DFB	Dual fluidised bed
DOE	Design of Experiment
EFB	Empty Fruit Bunch
EPA	Environmental Protection Agency
ER	Equivalence ratio
ER-Based	Equivalence ratio based
FC	Fixed carbon
GHG	Greenhouse gas
GZ	Gasification zone
HHV	Higher heating value, kJ/kg or MJ/kg
ktoe	kilotonne of oil equivalent
LHV	Lower heating value, kJ/kg or MJ/kg
MC	Moisture content
NG	Napier Grass
NS	Navier-Stokes
OFAT	One factor at a time
OPF	Oil palm fronds
OPT	Oil palm trunks
PKS	Palm Kernel shell
RSM	Response surface methodology
SBH	Static Bed Height
SBH-Based	Static bed height based
STBR	Steam to biomass ratio
T-Based	Temperature based
VM	Volatile matter

LIST OF SYMBOLS

C_d	drag coefficient
C_p	Specific heat capacity, kJ/kg K
D	diameter
Ds	Diffusion coefficient, m2/s
d_p	Particle diameter
ε	porosity
E_a	Activation energy, J/mol
g	acceleration of gravity
$\overline{h_{f,i}}$	Molar enthalpy of formation of gaseous component *i*, J/mol
k	turbulent kinetic energy
K	Temperature unit, Kelvin
mw	Molecular weight, kg/kmol
$\dot{m}$	Mass flow rate, kg/s
MWe	Megawatt electrical
n	Molar flow rate, kmol/s
η_T	Thermal efficiency
P	Pressure, pa
ΔP	pressure drop
Pr	Prandtl number
Q	gas volumetric flow rate, m^3/hr or sqft/hr
$Ø$	granular temperature, K
Rg	Universal gas constant, J/mol K
Re	Reynolds number
T	Temperature, °C or K
$\bar{\bar{t}}$	stress tensor
U	gas superficial velocity, m/s
Wt.%	weight percent
ZnO	Zinc oxide

CHAPTER 1

INTRODUCTION

1.1 Biomass as Renewable Energy Resource

Biomass for years has gained major interest as a source of renewable energy for its significance in sustainable energy and environmental friendly aspects. The importance of biomass energy is mostly upon its utilization in replacing fossil fuels and reducing the dependency of the energy consumption to those sources (Mohammed et al., 2011; Ruiz et al., 2013). There are various types of biomass, however the most commonly used one is wood in its different forms e.g. trunks, fronds, sawdust and forest residues (Kim et al., 2013). Feedstock selected for this study is *Pennisetum purpureum*, also known as Napier grass, elephant grass or Uganda grass (Farrell et al., 2002). The selection of Napier grass is due to a numerous benefits attributed including high dry matter, fast growth rate and propagation, relatively high colorific value and adaptability (Boon et al., 2017).

Although traditional biomass combustion tends to have lower efficiencies in terms of power and electricity generation and limited supply comparing to the fossil, however its advantages of providing an economical and sustainable technology makes it significant enough to be considered in high priorities. The regarded issue of low energy efficiency attributed by biomass combustion, compensates to some extents with the technology of gasification while coupled with advanced power generating systems such as diesel generators (syngas injects as a supplementary source) or gas turbines (Asadullah, 2014).

Gasification is a thermochemical converting method in which the bio-based feedstocks converts to synthesis gas (syngas) and the by-products form at subsidiary stages of the process. Gasification occurs once a preheated oxidizer known as ‘gasification agent’ (i.e. air/steam) introduced into the reactor and the temperature of the reactor raised to a certain level (above 700°C). The moisture level of biomass drops at the beginning of the operation and the volatile matter releases subsequently. The carbon content from the feedstock as well as the hydrocarbons from the volatiles start to crack and the inherent energy involved in the biomass converts it to the combustible gas (McKendry, 2002c). Figure 1.1 shows the stages of the operation to produce the final syngas which involves in three major steps of gasification itself, condensation and gas-cleaning. In each step the specific by-product and condensate gets separated and collects to use in related applications.

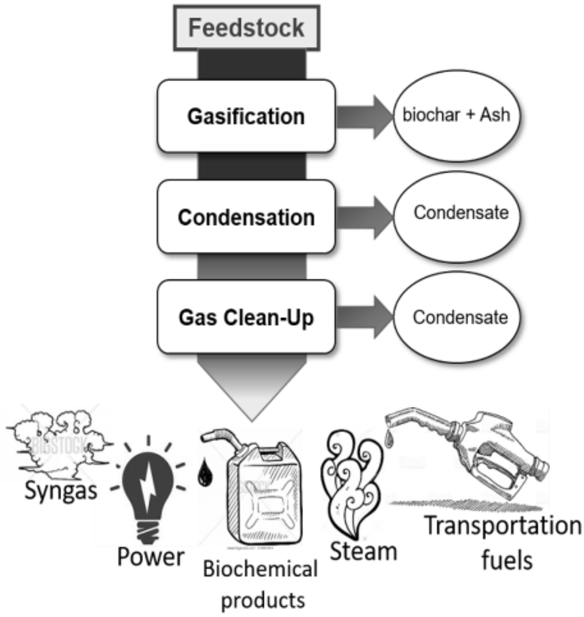

Figure 1.1: Schematic description of biomass gasification and its products. Source**:** (Ruiz et al., 2013)

The proposed reactor for this study is an auto-thermal bubbling fluidized bed with output power capacity of 5 kilo watts. In auto-thermal processes, part of the energy content of the fuel which releases during partial combustion is used to keep an endothermal process running, therefore the required energy provides from the process itself and without the requirement for any external sources. In economic point of view, the regarded fact may considered a huge saving of resources however from the technical angle, it introduces several difficulties and limitations that must be mitigated. Start-up heating in an auto-thermal biomass gasification is typically implemented by combusting bio-based material which may take a long period for the reactor to reach its operating temperature. Moreover, the temperature in auto-thermal process is usually controlled by the adjustment of ratio between the inlet air and biomass feeding therefore the process is typically instable and imposed with high level of fluctuations. Once the mentioned issues are resolved and the process becomes steady, the auto-thermal gasification technology can be integrated with an internal combustion engine to be used in electricity generation for rural area where having limited access to electricity grids.

The fluidization of particulate solids takes place in fluidized bed reactor. Fluidization is entitled for the phenomenon in which a fluid (liquid or gas) passes through a bed of granular solid and converts the static bed to the dynamic state. Fluidized bed reactors are credited by many industries for several advantages including uniform temperature distribution, fine gas-solid mixing characteristics and much higher rates of mass and energy transfer comparing to fixed bed types (Wang et al., 2008).

The exploration of physics related to biomass fluidization is still an interesting and fairly noble topic for many researches and investigations. The complexity involved in the fluid-solid interactions especially while considering in gasification, appeals a well-defined knowledge to describe the fluidization behavior. A model of which accurately describes the fluidization phenomena is capable to predict the quantities and to estimate how the system reacts if imposed to any probable variations of parameters such as pressure drop, superficial and minimum fluidization velocities.

The understanding of fluidization hydrodynamic is necessary in order to improve the operation and yet difficult to achieve empirically. Depending on the different characteristics of materials (in terms of physical geometry, sizes, densities etc.), several parameters has to be considered for the purpose of analysis. An accurate numerical model can describe the phenomenon for any type of material used (Baruah & Baruah, 2014). Silica sands are cost effective and are favorable to use as bed medium in high temperature gasification as they provide a uniform fluidizing bed (McKendry, 2002c).
There are number of issues important to address for one dealing with air gasification:

i. The calorific value (CV) of the producer gas in air gasification is relatively lower than steam gasification as the producer gas is diluted by nitrogen introduced with inlet air.(Asadullah, 2014)
ii. Air gasification results to lower CV of the producer gas; it is more preferable to use directly in combustion or as a supplementary source in diesel engines. If the target is to use the syngas in bio-chemical production such as methanol and methane, hence air gasification is not the desirable technology.
iii. Slagging and agglomeration are common issues associated with fluidized bed gasification due to the ash content of the biomass. One of the practical treatments to avoid slagging is to keep the bed temperature at lower degree, which however results to further loss of char (McKendry, 2002c).

1.2 Problem Statement

Biomass gasification although considered one of the crucial sustainable alternatives for carbon-based energy sources, the currently used technologies are not yet as efficient and powerful as expected to be. There exists a number of common and technology-specific limitations which make biomass gasification a complex and sensitive process such as the instable operation, handling of residues, fuel preparation, the cost of set-up and maintenance and the proper-state of the producer gas in terms of chemical and physical properties. The drawbacks are even more emphasized when dealing with auto-thermal reactor as it introduces a number of further consideration related to start-up heating and preparation. Auto-thermal gasification as explained before, although brings along several handling and operating difficulties, it reduces a huge amount of capital and operating cost since the required heat for carbon conversion is supplied from exothermic chemical reactions within the reactor. The importance of auto-thermal gasifier is even more highlighted as it uses for the purpose of electrification in rural area whereby restricted from the access to electricity grids.

Reactor optimization is one of the techniques in mitigation of deficiencies imposed by auto-thermal process. Several operating parameters are previously identified to have significant influence on gasification such as feeding rate, equivalence ratio, reactor temperature and static bed height. Any variation of those parameters may affect the quality of the producer gas as well as the performance of the operation. In addition, different characteristics of feedstocks e.g. thermo-chemical properties, carbon content, bulk density etc. may also results in different outputs. An optimum range of variation for such parameters must be determined in order to achieve the desirable products.

There exists a number of physical parameters to have significant influence on gasification and thus should be considered, however they are difficult to measure through experimentations. Parameters related to particle interactions and fluidization hydrodynamics are the instances of those which seem to be expensive and time consuming to determine empirically. An accurate numerical hydrodynamic evaluation can play a crucial role to overcome such problems and to investigate important factors such as superficial velocity, formation of bubbles, motion pattern of particles, expansion ratio of bed materials and other related factor that influence the hydrodynamics of fluidization and hence the yield and quality of products as the result.

Another important concern especially while dealing with auto-thermal reactor is regarding the unsteady and hard to control temperature variation that takes place during the operation. High fluctuations in temperature may lead up to dangerous or undesired situations such as high pressure, runaway reaction and explosion in case of high temperature or high amount of tar and low amount of combustible species in products in case of low temperature conditions. It has not yet observed a comprehensive numerical study from the literatures to address the temperature profile and heat distribution in an auto-thermal fluidized bed gasifier and the gap is still exists in this particular area of concern. A proper process simulation verified with actual data can generate temperature profiles at each time step of the operation and therefore provide the feasibility to monitor and control the process at any time.

Once the challenges related to instable and complex operation has been overcome and the process has been optimized with the help of numerical models and experimental analysis, the technology can be further improved for scale-up.

1.3 Aim and Objectives

The objectives of this study can be enlisted as following:

1. To perform the optimization of the autothermal gasifier through investigating the effect of operating parameters on the producer gas in terms of yield and combustibility.
2. To determine the effect of factors related to hydrodynamics of fluidization and motion of the particles through computational fluid dynamic modeling and simulation
3. To evaluate the heat distribution inside the reactor and investigate the effect of parameters on the temperature profile through thermodynamics modeling and simulation.

1.4 Scope of Work

The scope of work for this study is divided in three main sections according to the objectives:

1- For the first objective, biomass characterization was completed and minimum fluidization velocity was calculated through experimental approach. This study was conducted to perform sensitivity analysis on gasification of Napier grass in an auto-thermal bubbling fluidized bed reactor using two experimental designs of:

i- One factor at the time (OFAT). This approach was performed to investigate the influence of main operating parameters on the producer gas and was included two main steps, namely OFAT-A and OFAT-B. OFAT-A studied the effect of temperature, equivalence ratio and static bed height on the composition of syngas with the target of achieving compositions of hydrogen and carbon monoxide and lowest composition of carbon dioxide. OFAT-B studied the effect of temperature, equivalence ratio and static bed height on yield of products with the target to achieve the highest yield of syngas (flowrate) and lowest production of liquids (tar and bio-oil) and residues (ash and char).

ii- The application of Response surface methodology (RSM) was studied to evaluate the interactions of parameters with the method of Box-Behnken. The selected independent factors were temperature, static bed height and equivalence ratio and the respected responses were the syngas yield (mole %) and tar yield (wt %). An optimization method of “The desirability approach” was used to identify the optimum operating conditions.

2- Computational fluid dynamics (CFD) with ANSYS Fluent framework was used to simulate the hydrodynamics of gas-solid mixing and fluidization. The 2D simulation was performed based on defined geometry, boundary conditions, generated mesh and wall functions. The effect of fluid regimes (laminar flow, RNG k-Ɛ and K-ω turbulent flows) as well as the effects of superficial velocity, air distributor with different pore sizes, drag models and pressure drop was investigated on the bed expansion, bubble formation and flow motion pattern. The pressure drop model was validated by experimental data to ensure that the simulated case is capable to represent the actual process.

3- Computational fluid dynamics (CFD) with ANSYS Fluent framework was used to perform the heat transfer models. The heat distribution inside the reactor was modelled based on the obtained hydrodynamics characteristics. The formulation of total energy was modified and added by a term (S_h) to describe the variation of energy due to enthalpies of chemical reaction related to gasification in equilibrium state. The degradation of a single particle of Napier grass as inserted in a reactor with fluidizing bed at gasification temperature was simulated and the degradation rate was calculated. The effect of different biomass particle sizes and initial bed temperatures on biomass degradation rate and consequently on temperature profile in gasifier was investigated. The temperature values from the simulation data was validated by those recorded from the thermocouples on reactor used in experimentation at the same operation state to ensure that the calculation of total energy is accurate and the model is representing the actual process.

1.5 Limitations

This study was imposed with a number of restrictions as below:

i. Limitations caused by handling and control: since the instrumentations has been designed with the target of setting up a simple procedure to become economic and with least complexity of operation for the users. The apparatus for this study was selected as auto-thermal to avoid the excess costs related to heating. The source of heating is provided from the energy release through exothermic reactions of cracking and oxidizing of carbon components. The regarded fact creates instability and hence, difficulties to handle the operation at the set points of parameters mostly emphasized for temperature as it encounters consistent fluctuations.

ii. Limitations caused by equipment design and mechanism of operation: The intention for considering economic aspects over the whole design stages imposed a few restrictions including the essential to avoid using expensive feedstock materials, complex catalysts or any operational conditions that considered costly.

1.6 Thesis Structure

This thesis consists of five chapters following the structures. Chapter One provided knowledge about significance of biomass gasification and the scope of current research, moreover emphasized on the objectives taken to overcome the research problem. Chapter Two provides a detailed review on literatures related to various experimental and numerical approaches on gasification of biomass and fluidization of solid particles. Research methodology has been comprehensively explained in Chapter Three divided by two parts of experimental and numerical approaches. The final results have been presented and discussed in detail in Chapter Four and the correlation of quantities and validation of models has been performed and justified. Chapter Five is the final conclusions to highlight the most significant aspects and outcomes from the research.

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