EFFICIENCY IMPROVEMENT OF NRMM'S FC-BATTERY POWERTRAIN IN COLD WEATHER WITH PCM-BASED WASTE HEAT RECOVERY

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MASTER OF MECHANICAL ENGINEERING (AUTOMOTIVE)

2024

Faculty of Technology and Mechanical Engineering

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A master project submitted in partial fulfillment of the requirements for the degree of Master of Mechanical Engineering (Automotive)

Faculty of Technology and Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

DECLARATION

I declare that this master project entitled "Efficiency Improvement of NRMM's FC-Battery Powertrain in Cold Weather with PCM-Based Waste Heat Recovery" is the result of my own research except as cited in the references. The master project has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :..

Name : Ahmad Syamil bin Ulul-Azmin

Date :29 September 2024

APPROVAL

I hereby declare that I have read this master project and in my opinion this master project is sufficient in terms of scope and quality as a partial fulfillment of Master of Mechanical Engineering (Automotive).

Signature : ....

UTeM's Supervisor Name : Professor Ts. Dr. Noreffendy bin Tamaldin

Date :16 November 2024

Signature : ....

FH Aachen's Supervisor Name : Professor Dr-Ing. Thomas Esch

Date : AACHEN, 2.10.24

DEDICATION

This thesis is dedicated to my beloved parents, whose unwavering support, encouragement, and love have been my greatest source of strength and motivation throughout this journey. To my friends and mentors, thank you for your guidance and belief in me. This accomplishment would not have been possible without all of you.

ABSTRACT

This thesis focuses on enhancing energy efficiency in Non-Road Mobile Machinery (NRMM) powertrains for operating in cold climates by utilizing FC (FC) -battery powertrain system. This research investigates the effectiveness of proposed heating system which utilize FC coolant's heat for waste heat recovery (WHR) system through phase change material (PCM) application in outperforming conventional heating system which use Positive Temperature Coefficient (PTC) heater in preheating FC, battery and cabin during operation under cold weather. This proposed heating system can address significant heat loss from FC stack and high-power demand by PTC heater, hence enabling powertrain to reduce reliance on PTC heater. Using GT-Suite software, a full system model which incorporates subsystems like FC, battery, propulsion and hydraulic systems integrated with conventional and proposed heating systems was developed and simulated. Two simulations were run to compare the conventional and proposed system during startup and middle NRMM operation respectively during cold weather. Results showed the uses of proposed PCM-based WHR system on subsequent working day able to reduce up to 51.12% of energy consumption on auxiliary loads, give 7.5 minutes faster preheating time, eliminate mismatches between heat supply and demand and offer higher final battery SOC level on FC-battery powertrain system. Ultimately, this study demonstrates that advanced WHR through PCM significantly improves the powertrain's energy efficiency in cold weather thus offering a practical solution for NRMM applications. Future recommendations include experimental validation and techno-economic analysis for system performance verification and cost-effectiveness evaluation.

Peningkatan Prestasi Rangkaian Kuasa Hibrid Sel Bahan Api-Bateri NRMM ketika Cuaca Sejuk dengan Pemulihan Haba Berasaskan PCM

ABSTRAK

Tesis ini menumpukan kepada peningkatan kecekapan tenaga dalam rangkaian kuasa Jentera Bergerak Bukan Jalan Raya (NRMM) untuk beroperasi dalam cuaca sejuk dengan mengintegrasikan sistem hibrid sel bahan api (FC) dan bateri. Penyelidikan ini mengkaji keberkesanan sistem pemanasan yang dicadangkan iaitu menggunakan haba penyejuk FC untuk sistem pemulihan haba buangan (WHR) melalui aplikasi bahan perubahan fasa (PCM) dalam mengatasi sistem pemanasan konvensional yang menggunakan pemanas Pekali Suhu Positif (PTC) bagi pemanasan awal FC, bateri dan kabin semasa operasi dalam cuaca sejuk. Sistem pemanasan yang dicadangkan ini dapat menangani kehilangan haba yang ketara daripada operasi FC dan permintaan kuasa tinggi oleh pemanas PTC, sekaligus membolehkan rangkaian kuasa mengurangkan kebergantungan pada pemanas PTC. Dengan menggunakan perisian GT-Suite, satu model sistem penuh yang menggabungkan subsistem seperti FC, bateri, sistem pendorongan, dan sistem hidraulik yang diintegrasikan dengan sistem pemanasan konvensional serta sistem yang dicadangkan telah dibangunkan dan disimulasikan. Dua simulasi dijalankan untuk membandingkan sistem konvensional dan sistem yang dicadangkan semasa operasi permulaan dan operasi pertengahan NRMM ketika cuaca sejuk. Hasil kajian menunjukkan bahawa penggunaan sistem WHR berasaskan PCM yang dicadangkan mampu mengalahkan sistem pemanasan konvensional pada hari kerja berikutnya iaitu dapat mengurangkan 51.12% penggunaan tenaga pada beban tambahan, mempercepatkan masa pemanasan awal sebanyak 7.5 minit, dan memberikan tahap caj (SOC) akhir bateri yang lebih tinggi pada sistem rangkaian kuasa hibrid FC-bateri. Secara keseluruhannya, kajian ini membuktikan bahawa pemulihan haba buangan melalui aplikasi PCM meningkatkan kecekapan tenaga rangkaian kuasa dalam cuaca sejuk secara signifikan sekali gus menawarkan penyelesaian praktikal untuk aplikasi NRMM. Cadangan kajian pada masa hadapan termasuk pengesahan eksperimental dan analisis tekno-ekonomi untuk pengesahan prestasi sistem serta penilaian keberkesanan kos.

ACKNOWLEDGEMENT

In the Name of Allah, the Most Gracious, the Most Merciful. First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my main and co-supervisors at UTeM, Prof. Ts. Dr. Noreffendy bin Tamaldin and Dr. Ahmad Kamal bin Mat Yamin, for their constructive feedback and continuous support throughout the duration of this research. Their expertise and advice have been instrumental in steering this work toward successful completion.

My profound appreciation goes to Prof. Dr.-Ing. Thomas Esch and Mr. Aezid UL Hassan Najmi from FH Aachen University, Germany, for their supervision and mentorship during my research at their university. Their knowledge and expertise significantly contributed to the development of this work, and their guidance was integral to the success of this thesis.

I would like to express my gratitude to both UTeM and FH Aachen University for providing me with the opportunity to participate in the student mobility program for conducting this thesis, which greatly enriched my academic and research experience as well as facilitated the completion of this thesis. Special thanks to FH Aachen University for providing the licensed GT Suite software, which was a critical tool for conducting the necessary simulations and analyses throughout this research.

I would also like to acknowledge the contributions of my research teammates at FH Aachen, whose valuable suggestions and collaborative efforts greatly enriched this thesis. Their ideas and supports were essential in overcoming various challenges during this project.

Finally, I extend my heartfelt gratitude to my family and friends for their unwavering encouragement, patience, and support, which have been a constant source of strength throughout this journey.

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LIST OF ABBREVIATIONS

CFD	-	Computational Fluid Dynamic
DCV	-	Directional Control Valve
EMS	-	Energy Management Controller System
FC	-	FC
FSM	-	Finite State Manager
HX	-	Heat Exchanger
NRMM	-	Non-Road Mobile Machinery
PCM	-	Phase Change Material
PCM − HX	-	PCM-Embedded Heat Exchanger
PEMFC	-	Proton Exchange Membrane FC
PID	-	Proportional-Integral-Derivative
PTC	-	Positive Temperature Coefficient
SOC	-	State of Charge
WHR	-	Waste Heat Recovery

LIST OF SYMBOLS

$Q(t)$	-	Current electric charge stored in battery
Q_c	-	Total battery capacity
P	-	Hydraulic power
Q	-	Volumetric flowrate
p	-	Hydraulic pressure
D	-	Pump displacement
N	-	Pump Speed
f_d	-	Displacement fraction
η_v	-	Volumetric Efficiency
P_{dem}	-	Total power demand
P_{batt}	-	Battery power
P_{FC}	-	Fuel Cell power
Q	-	Heat transfer rate
$\dot{m}$	-	Mass flow rate
C_p	-	Specific heat capacity at constant pressure
ΔT	-	Temperature difference
Q_1	-	Inlet air flow rate
Q_2	-	Outlet air flow rate
A_1	-	Inlet cross-sectional area
A_2	-	Outlet cross-sectional area
v_1	-	Inlet air speed
v_2	-	Outlet air speed

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CHAPTER 1

INTRODUCTION

1.1 Background

The proposed master's thesis extends the expanding significance of energy-efficient Non-Road Mobile Machinery (NRMM) powertrains in cold weather through waste heat recovery (WHR) implementation. Given the fact that NRMM works in a variety of environments, including cold climates, it is critical to consider the effect of low temperatures towards fuel cell (FC) and battery performance as well as power requirement for cabin heating which require Positive Temperature Coefficient (PTC) heater for conventional operation. The study is driven by the need to design inventive resolutions that improve energy efficiency without compromising dependable functionality amidst severe cold weather circumstances.

In accordance with this need, the study aims to ascertain possible options for conserving energy by means of WHR application through the utilization of Phase Change Material (PCM) which can store waste heat from FC coolant and acting as thermal storage system thus minimizing the reliance on PTC heater. PCMs are selected for waste heat recovery because of their high energy storage capacity at constant temperatures which gives stable thermal management. Their adaptable melting points suit specific operating ranges, and they provide high energy density in compact spaces. Unlike sensible heat materials, PCMs effectively handle cyclic heating loads, making them ideal for NRMM. Furthermore, they are more cost-effective than advanced alternatives hence offering an optimal balance of performance, stability, and cost.

The study scope that has been chosen utilises sophisticated modelling approaches, particularly the 1D modelling tool GT-Suite, which is well recognised for its capability to simulate automotive systems. By using this technique, a thorough examination of FC-battery powertrain system will be conducted, considering several subsystems that are vital for NRMM applications, specifically wheel loader. Through a comprehensive engineering approach, possible imbalances between heat supply and demand within the system are attempted to be resolved from the simulation inside GT Suite. The efficiency improvement of this type of powertrain system will be evaluated by observing the comparison of power demand between conventional heating system which use PTC heater and proposed novel heating system which use PCM within this powertrain system.

In brief, this study fills a significant need in the field of NRMM powertrains by presenting an innovative strategy to improve energy efficiency during periods of extreme cold weather condition. The predicted results are projected to provide a substantial contribution to the continuous efforts of creating sustainable and efficient solutions for NRMM applications, in line with the worldwide movement towards environmentally friendly and energy-efficient technology.

1.2 Problem Statement

Literature-based problems regarding research on FC efficiency and WHR include the following:

i. Based on previous literatures, the heat loss from FC's operation that released to surrounding as waste heat are in significant amount thus reducing efficiency of powertrain system.

ii. During cold weather where the temperature is below zero, the FC and battery have limited operation during startup operation thus lowering their efficiency in providing power to powertrain system as well as affecting their lifespan. This triggers the requirement of preheating mechanisms for both components to ensure they can consistently operate at optimum temperature.

iii. Conventional FC, battery and cabin heating mechanism use PTC heater, which consume power from powertrain, leading to high power consumption for auxiliary loads thus reducing NRMM's operation or driving range.

iv. The lack of adequate engineering assistance concerning the effective utilisation of FC waste heat and possible discrepancies between heat supply and demand within the system pose a significant barrier to the development of a functional and optimised powertrain for a hybrid battery-FC NRMM designed for cold weather operations.

Therefore, the objective of this research is to resolve the issues pertaining to the efficiency of FC in cold weather by developing an innovative, energy-efficient FC-battery powertrain system for NRMM applications that makes full use of the waste heat from FC operation.

1.3 Research Objectives

The overarching aim of this research is to develop an innovative energy-efficient FC-battery powertrain system for NRMM applications in cold weather conditions, with a particular emphasis on FC waste heat recovery. The objectives accompanying this aim are thus to:

i. analyze energy saving opportunities based on WHR using PCM within the system to enhance the overall energy efficiency of a hybrid battery-FC powertrain system.

ii. design and implement novel preheating strategies for FC and battery using WHR system to ensure minimization of PTC heater power consumption

iii. develop a feasible engineering solution by taking a holistic system level approach for effective utilization of FC heat while considering possible mismatches between heat supply and demand within the system.