

Numerical and Experimental Studies on Organic Rankine Cycle for Low-Medium Waste Heat Sources



Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

By

Mayank Srivastava

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI-221005
INDIA

20131510

2024

CERTIFICATE

It is certified that the work contained in the thesis titled “**Numerical and Experimental Studies on Organic Rankine Cycle for Low-medium Waste Heat Sources**” by **Mr. Mayank Srivastava** has been carried out under our supervision and that this work is not submitted elsewhere for any degree.

It is further certified that the student has satisfactorily fulfilled all the requirements of the Comprehensive examination, Candidacy and SOTA for the award of the Ph.D. degree.



Prof. Jahar Sarkar

(Supervisor)

Department of Mechanical Engineering

IIT (BHU) Varanasi

प्रध्यापक / Professor
कृत्तिका अभियांत्रिकी विभाग/Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान/Indian Institute of Technology
(काठिंडीवि०/B.H.U.)
वाणनसि-२२१००५/Varanasi-221005



Prof. Arnab Sarkar

(Co-supervisor)

Department of Mechanical Engineering

IIT (BHU) Varanasi

प्रध्यापक / Professor
कृत्तिका अभियांत्रिकी विभाग/Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान/Indian Institute of Technology
(काठिंडीवि०/B.H.U.)
वाणनसि-२२१००५/Varanasi-221005

DECLARATION BY THE CANDIDATE

I, **Mayank Srivastava**, certify that the work embodied in this thesis is my own bonafide work carried out by me under the supervision of **Prof. Jahar Sarkar** and **Prof. Arnab Sarkar** for a period of 4 years from January 2021 to December 2024 at IIT (BHU), Varanasi. The material contained in this thesis has not been submitted for the award of any other degree. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any others work, paragraphs, text, data, results, etc. reported in journals, books, magazines, reports, dissertations, thesis, etc. or available at website and have not included them in this thesis and have not cited as my own work.

Date: 16/12/2024

Place: IIT (BHU), Varanasi



(Mayank Srivastava)

DECLARATION BY THE SUPERVISORS

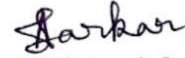
This is to certify that the above statement made by the candidate is correct to the best of my knowledge.



Prof. Jahar Sarkar

(Supervisor)

प्राध्यापक / Professor
संशोधन विभाग / Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान / Indian Institute of Technology
(काठिंडी / B.H.U.)
वाराणसी - 221005 / Varanasi-221005



Prof. Arnab Sarkar

(Co-supervisor)

प्राध्यापक / Professor
संशोधन विभाग / Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान / Indian Institute of Technology
(काठिंडी / B.H.U.)
वाराणसी - 221005 / Varanasi-221005



Head of the Department

Mechanical Engineering Department, IIT (BHU), Varanasi

संशोधन विभाग / Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान / Indian Institute of Technology
(काठिंडी / B.H.U.)
वाराणसी - 221005 / Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Numerical and Experimental Studies on Organic Rankine Cycle for Low-medium Waste Heat Sources.

Candidate's Name: Mayank Srivastava

COPYRIGHT TRANSFER

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the "*Doctor of Philosophy*" degree.

Date: 16/12/2024

Place: IIT (BHU), Varanasi



(Mayank Srivastava)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and University's copyright notice are indicated.

ACKNOWLEDGEMENTS

I take this opportunity to express my deep sense of gratitude 🙏 to my supervisor **Prof. Jahar Sarkar** for their continuous guidance and whole-hearted cooperation in carrying out this work. His meticulous and valuable review and constructive criticism of the manuscript have greatly improved the quality of work. Sir, for your faith in me and the desire to live up to your expectations, has constantly pushed me to work harder. I would extend my gratitude to my co-supervisor **Prof. Arnab Sarkar** for his support at all stage of research activity.

My grateful appreciation also goes to **Dr. S. S. Mondal** and **Dr. J. P. Chakraborty** for serving on my research progress evaluation committee (RPEC). Thank you all for sparing your valuable time and assisting me throughout my research and completion of this thesis. I wish to extend my sincere thanks to **Prof. Sandeep Kumar**, Head, Department of Mechanical Engineering for providing me the necessary resources to enable me to complete this research work. During my stay at IIT (BHU) Varanasi, I have met many people who have made this period of my life memorable and very pleasant. Among them, I would like to sincerely acknowledge the assistance and motivation provided by **Prof. Rashmi Rekha Sahoo**, **Prof. J. V. Tirkey**, and **Prof. Amitesh Kumar**. I want to thank my seniors at IIT (BHU) Varanasi, especially to **Dr. Mayaram Sahu**, **Dr. Prashant Srivastava**, **Dr. Satish Upadhyay**, and **Dr. Archana Kumari** and my colleagues **Mr. Harendra Kumar Yadav**, **Mr. Aishwary Pratap** and **Mr. Ujjawal Kumar Singh** for encouraging me to finish this work. My precious moral support, other than IIT (BHU) Varanasi, were **Mr. Rakesh Singh**, **Mr. Ashish Kumar Yadav**, **Mr. Piyush Srivastava**, **Mr. Shailesh Vishwakarma**, **Mr. Vishal Srivastava**, and all my other beloved ones whose continuous motivation made me stronger. The experimental part of this thesis has been carried out at the Department of Mechanical Engineering IIT (BHU) Varanasi. A number of persons have assisted and supported me in designing and development of the test rig. I would like to extend my sincere thanks to **Mr. Moolchand** and **Mr. Barmeshwar Prashad** for giving the valuable ideas while performing experiments and

providing the measurement tools and instruments whenever needed for the research work without any hesitation.

I wish to express my profound and heartfelt gratitude to my dearest parents 🙏 - my father, **Mr. Mahendra Pratap Srivastava**; my mother, **Mrs. Uma Srivastava**; and my cherished sister, **Mrs. Shalu Srivastava**. Their unconditional love, selfless sacrifices, constant emotional encouragement, belief in my potential and unwavering financial support have been the foundation and gave me strength, upon which my academic and personal growth has flourished. This work is a testament to your profound sacrifices, and my heart overflows with eternal gratitude. I would like to extend my gratitude to my paternal and maternal family members, as well as my friends, for their constant support, faith, and love.

I also wish to extend my heartfelt gratitude to the Almighty **Lord Vishwanath/Mahadev** 🙏 for bestowing upon me the strength and divine guidance to stay steadfast on my path to success.

Date: 16/12/2024

Place: IIT (BHU), Varanasi



(**Mayank Srivastava**)

List of Figures

Figure 1.1. Layout and temperature-entropy diagram of waste heat recovery ORC.....	2
Figure 2.1. Layout and T-s diagram of ORC with dry working fluid.....	18
Figure 2.2. Layout and T-s diagram of ORC with wet working fluid	19
Figure 2.3. Layout and T-s diagram of CO ₂ Rankine cycle.....	20
Figure 2.4. Layout and T-s diagram of Kalina cycle	21
Figure 2.5. Layout and T-s diagram of OFC	22
Figure 2.6. Layout and T-s diagram of TFC.....	23
Figure 2.7. Flow chart of the simulation procedure.....	31
Figure 2.8. Component irreversibility of different cycles at 90°C	36
Figure 2.9. Exergy analysis of different cycles at 90°C source temperature.....	37
Figure 2.10. Variation of net work output with heat source temperature	38
Figure 2.11. Variation of thermal efficiency with heat source temperature	39
Figure 2.12. Variation of exergy efficiency with heat source temperature	39
Figure 2.13. Variation of annual total cost required with heat source temperature.....	40
Figure 2.14. Variation of total annual profit with heat source temperature.....	41
Figure 2.15. Variation of annual CO ₂ saving with heat source temperature.....	42
Figure 3.1. Schematic layout of proposed EEORC-1	50
Figure 3.2. Temperature-entropy diagram of proposed EEORC-1.....	50
Figure 3.3. Schematic layout of proposed EEORC-2.....	51
Figure 3.4. Temperature-entropy diagram of proposed EEORC-2.....	52
Figure 3.5. Flow chart of the simulation procedure for EEORC	55
Figure 3.6. Effect of waste heat inlet temperature variation on net work output	61
Figure 3.7. Effect on ejector pressure with the variation of waste heat inlet temperature.....	62
Figure 3.8. Improvement of net work output with waste heat inlet temperature.....	63
Figure 3.9. Effect on thermal efficiency with waste heat inlet temperature	64
Figure 3.10. (a) Effect on entrainment ratio by variation of WHT, (b) Effect of PLR by the variation of WHT for different cycles	65
Figure 3.11. Irreversibility value of different cycle components at 70 °C	66
Figure 3.12. Effect on exergy efficiency with WHT for different cycles.....	67
Figure 3.13. Effect on size parameter of turbine with WHT for different cycles.....	68
Figure 3.14. Effect on total evaporator and condenser areas with WHT for different cycles .	69

Figure 3.15. Value comparison on components cost rate of different cycles at 70 °C.....	70
Figure 3.16. (a) Variation on total profit and selling price of EEORC-1 (R123) with WHT, (b) Variation on net annual profit with WHT for different cycles and working fluids.	72
Figure 3.17. Variation of CO ₂ saved with WHT for different cycles and working fluids.....	73
Figure 4.1. Layout of the experimental setup for the Organic Rankine Cycle	76
Figure 4.2. (a) Fabrication of the vertical separator and (b) modification of the scroll compressor to expander.....	77
Figure 4.3. (a) Fabrication of the heating load and control unit with oil tank, (b) Pressurized storage tank for working fluid	79
Figure 4.4. Installation of instruments and sensors to ORC setup.....	81
Figure 4.5. Lab-scale ORC experimental setup	84
Figure 4.6. Isometric view and running condition of ORC experimental setup	86
Figure 4.7. Normal plot of variation between predicted and actual value of net power and cycle efficiency.....	94
Figure 4.8. Effect on (a) Evaporator temperature and (b) Mass flow rate of working fluid....	95
Figure 4.9. Effect on (a) expander inlet temperature and (b) expander outlet temperature.....	96
Figure 4.10. Effect on pressure ratio of (a) pump and (b) expander.....	98
Figure 4.11. Effect on isentropic efficiency of (a) pump and (b) expander.....	99
Figure 4.12. Effect on (a) net power output and (b) cycle efficiency	100
Figure 4.13. Effect on (a) exergy and (b) exergy efficiency.....	102
Figure 4.14. Desirability for net power and cycle efficiency for prediction analysis.....	104
Figure 5.1. Alternator's capital cost correlation by trendline analysis between capacity (kW) and market price (USD)	119
Figure 5.2. Flowchart of simulation process for feasible location in NPP to install ORC	120
Figure 5.3. Schematic diagram of suggested ORC to be installed at NPP waste heat recovery site	121
Figure 5.4. (a) ORC T-s diagram of case-1, (b) ORC T-s diagram of case-2.....	124
Figure 5.5. Effect of condenser and cold fluid inlet temperatures on net work output	126
Figure 5.6. Effect of condenser and cold fluid inlet temperatures on thermal efficiency.....	127
Figure 5.7. Effect of condenser and cold fluid inlet temperatures on NPV of total investment	128
Figure 5.8. Effect of condenser and cold fluid inlet temperatures on yearly profit.....	129
Figure 5.9. Effect of condenser and cold fluid inlet temperatures on LCOE	130
Figure 5.10. Effect of condenser and cold fluid inlet temperatures on DPP	131

Figure 5.11. Effect of condenser and cold fluid inlet temperature on IRR for different case cycles	132
Figure 5.12. Effect of the condenser and cold fluid inlet temperature on annual CO ₂ emission saving.....	133
Figure 5.13. T-s Diagram and layout of nanofluid based ORC	136
Figure 5.14. Net work comparison with different hot fluids and working fluids	138
Figure 5.15. Thermal efficiency comparison with different hot fluids and working fluids...	139
Figure 5.16. Working fluid mass flow rate comparison with different hot fluids and working fluids.....	140
Figure 5.17. Capital investment comparison with different hot fluids and working fluids ...	141
Figure 5.18. Earned profit comparison with different hot fluids and working fluids.....	142

List of Tables

Table 1.1. Literature review of experimental ORC's.....	9
Table 2.1. Component irreversibility calculation	24
Table 2.2. Heat exchanger area design	25
Table 2.3. Capital investment of system components [103,104].....	26
Table 2.4. Validation of different low/medium grade thermodynamic cycles	32
Table 2.5. Input parameters used for different thermodynamic cycle analyses.....	33
Table 2.6. Fluid properties for different thermodynamic cycles	33
Table 2.7. Comparison of optimized result outputs of various thermodynamic cycles at a source temperature of 90°C	34
Table 2.8. Effect of increasing and decreasing the T_{con} by 3°C on output parameters at a source temperature of 90°C	42
Table 2.9. Various challenges associated with thermodynamic cycles	44
Table 2.10. Comparison of solar ORC and solar P-V system [117].....	46
Table 3.1. Comparison of result obtained from reference with simulated values	56
Table 3.2. Selection of working fluids [119].....	56
Table 3.3. Input parameters for Basic and EEORCs	57
Table 3.4. Comparison of different cycles and working fluids at WHT = 70 °C.....	58
Table 4.1. ORC component description and technical details	80
Table 4.2. ORC sensors description, along with technical details.....	82
Table 4.3. ORC experimental data at various heat loads and mean input condition	89
Table 4.4. Uncertainty analyses of major input and output parameter	91
Table 4.5. Design of Experiment Table by Central Composite Method	92
Table 4.6. ANOVA coefficients and fit statistics of the model	93
Table 4.7. ANOVA optimization constraints	103
Table 4.8. Validation of optimized condition output result with the experimental run at same optimized condition.....	105
Table 4.9. Predicted data for net power and cycle efficiency in an ORC system, highlighting both experimental and theoretical predictions.....	106
Table 4.10. Advantages of current developed system with previously developed systems ...	106
Table 5.1. Waste heat disposal components and its temperature of Indian NPP data provided by BRNS.....	113
Table 5.2. Input condition data to check the feasibility of running ORC.....	114

Table 5.3. The market price of the alternator of different capacities and different manufacturer	117
Table 5.4. Recommended component design and specification for ORC installation	121
Table 5.5. Various input and output parameters for case 1 and case 2.....	122
Table 5.6. Effect on output parameter with working fluid for both feasible cases.....	125
Table 5.7. Simulation and experimental variation of Case-1 NPP	133
Table 5.8. Simulation and experimental variation of Case-2 NPP	134
Table 5.9. Input parameters used	136
Table 5.10. Thermophysical properties relevant to nanofluids [99,128].....	137
Table 5.11. Organic working fluid properties.....	137

List of Symbols

Abbreviation

EEORC	Ejector Enhanced Organic Rankine Cycle
OFC	Organic Flash cycle
ORC	Organic Rankine cycle
PLR	Pressure Lift Ratio
PPTD	Pinch point temperature difference
TFC	Trilateral flash cycle
WHT	Waste Heat source Temperature

Nomenclature

A	Area [m^2]
Bo	Boiling number
C	Cost [USD]
c	Velocity [m/s]
c_p	Specific heat [kJ/kg]
CRF	Capital recovery factor
D	Diameter [m]
Ex	Exergy [kW]
F	Fuel cost [USD]
G	Mass velocity ($\text{kg/s}\cdot\text{m}^2$)
h	Specific enthalpy [kJ/kg]
i	Interest rate
I	Irreversibility [kW]
k	Thermal conductivity [W/m-K]
l	Length/height [m]
LMTD	Log mean temperature difference [K]
\dot{m}	Mass flow rate [kg/s]
n	Number of years
OM	Operation and maintenance cost [USD]
P	Pressure [kPa]
Pr	Prandtl number
Q	Heat interaction [kW]

Re	Reynolds number
s	Specific entropy [kJ/kg-K]
SP	Size parameter
t	Thickness [m]
T	Temperature [°C]
$\dot{T}C$	Total cost rate [USD/h]
U	Overall convective heat transfer coefficient [W/m ² -K]
v	Specific volume [m ³ /kg]
W	Work transfer [kW]
x	Dryness fraction
z	Annual working hour [h]
Z ^{CI}	Capital investment cost [USD]

Greek letters

Σ	Sigma (sum notation)
α	Convective heat transfer coefficient [W/m ² -K]
β	Chevron angle
η	Efficiency
μ	Dynamic viscosity [N-s/m ²]
ρ	Density [kg/m ³]
ω	Entrainment ratio

Subscripts

1,2...12	State points
alt	Alternator
amb	Ambient
blr	Boiler
cf	Cold fluid
con	Condenser
d	Diffuser section of ejector
dp	Two-phase fluid
eje	Ejector
ele	Electricity
eq	Equivalent
evp	Evaporator

ex	Exergy
hf	Hot fluid
in	Inlet
ise	Isentropic
j	Any selected component
l	Saturated liquid state
liq	Liquid state
m	Mixing chamber of ejector
mix	Mixture
nz	Nozzle section of ejector
o	Outlet
pre	Preheater
pri	Primary
rec	Recuperator
req	Required
sec	Secondary
sep	Separator
sl	Saturated liquid state
sp	Single phase fluid
sub	Subcooled region
sup	Superheated region
sv	Saturated vapor state
t/tur	Turbine
th	Thermodynamic
thrt	Throttling
v	Saturated vapor state
vap	Vapor state
wet	Wet region (phase change)
wf	Working fluid