FLOW AND HEAT TRANSFER CHARACTERISTICS OF SUPERCRITICAL CARBON DIOXIDE IN MINI-CHANNELS

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JANUARY 2018

My Beloved Parents

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My Dearest Siblings

DR. DEVISRI NARASIMMA NAIDU

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My Respected Supervisors

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ACKNOWLEDGEMENTS

Firstly, all the praise and gratitude to Almighty God for giving good health and strength to me to complete my research successfully. Many people helped me throughout my research journey, there is no words to describe their contribution and time spent to help me to complete my project. Sincerely, I would like to thank each one of them and apologies for any of my mistake or behaviour.

Foremost, I would like to express my sincere gratitude to my supervisor and co-supervisor, Dr. Ahmed Nurye Oumer and Dr. Ummu Kulthum Jamaludin, respectively for the continuous support of my Master Degree study and research, for their patience, motivation, enthusiasm, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I am also thankful to Energy Sustainability Focus Group (ESFG) for giving me the advice and related comments and critics on my project to the extent of its completion. Without their outstanding support and interest, this thesis would not have been at the best it would right now.

Besides my advisor, I would like to express my deepest appreciation to my family whom had always support me financially and their never-ending motivations to ensure that I complete this project with least difficulty. Moreover, I would like to thank to my symposium panels, Dr. Firdaus Basrawi and Prof. Hassan Ibrahim for their guidance, suggestion, comment, and co-operation in this project. Besides that, I sincerely would like to thank to laboratory staff of Mechanical Engineering Department, UMP, who give permission to use the simulation software for my project analysis in order to complete my project.

Finally, to individuals who was involved either directly or indirectly in succession of this thesis. Indeed, I could never adequately express my indebtedness to all of them. Thank you.

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LIST OF SYMBOLS

A_s	Surface area
C	Coil diameter
C_p	Specific heat capacity at constant pressure
C_v	Specific heat capacity at constant volume
D	Tube diameter
$d/2$	Radius of inner tube
f	Friction factor
G	Mass flux
h	Heat transfer coefficient
ID	Inner diameter
j	J-factor
k	Thermal conductivity
L	Length
n	Number of turn for coil
Nu	Nusselt number
Nu_b	Bulk Nusselt number
p	Pitch of coil
P_{in}	Inlet pressure
P_{outlet}	Outlet pressure
Pr	Prandtl number
r_0	Height of outer tube
Re	Reynolds number
T_b	Bulk temperature
T_{in}	Inlet temperature
T_{out}	Outlet temperature
T_{pc}	Pseudocritical temperature
T_S	Surface temperature
T_W	Wall temperature
$\dot{m}_{in}$	Inlet mass flow rate
ρ	Density
μ	Viscosity
ΔP	Pressure drop
$\dot{Q}$	Heat transfer rate
$\dot{Q}_{conv}$	Convective heat transfer rate

T_∞	Temperature far from surface temperature
ε	Epsilon

LIST OF ABBREVIATIONS

2D	2-dimensional
3D	3-dimensional
AKN	Abe-Kondoh-Nagano
ANOVA	Analysis of variance
CCD	Central Composite Design
CFC	Chlorofluorocarbon
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
DAQ	Data acquisition system
DC	Direct current
DOE	Design of experiment
GMDH	Group method of data handling
HCFC	Hydrochlorofluorocarbon
HT	Heat transfer
HVACR	Heating, Ventilation, Air Conditioning, and Refrigeration
ID	Inner diameter
LRN	Low Reynolds number
MCHE	Micro-channel heat exchanger
MPa	Megapascal
NCL	Natural circulation loop
NI	National Instrumentation
NIST	National Institute of Standard and Technology
O_3	Ozone
ODE	Ordinary differential equations
PACO	Pressure Applied CO_2
PAG	Polyalkylene glycol
PCS	Power conversing system
PTFE	Polytetrafluoroethylene
RNG	Renormalization group
RS	Radiospare
RSM	Response surface method
$scCO_2$	Supercritical carbon dioxide
scH_2O	Supercritical water
SPHINX	Supercritical Pressure Heat Transfer Investigation for Next

	Generation
SST	Shear stress transport
YS	Yang-Shih
2D	2-dimensional

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JANUARY 2018

ABSTRAK

Sejak kebelakangan ini, karbon dioksida tahan kritikal ($scCO_2$) telah mulai digunakan dalam pelbagai aplikasi kejuruteraan, terumatanya dalam industri Pemanasan, Pengudaraan, Penyaman Udara dan Penyejukan (HVAC&R). Ini adalah kerana $scCO_2$ mempunyai sifat thermal yang unik dengan ciri-ciri permindahan haba dan aliran yang telah dipertingkatkan. Beberapa pemboleh ubah dari segi proses dan goemetri mempunyai kesan terhadap prestasi hidraulik dan haba $scCO_2$. Walau bagaimanapun, pemboleh ubah tersebut tidak diselidik sepenuhnya. Kajian ini telah dijalankan untuk menyelidik kesan-kesan pemboleh ubah proses (tekanan, suhu dan kadar aliran) dan geometri (diameter tiub) terhadap aliran dan permindahan haba $scCO_2$. Selain itu, ciri-ciri pemindahan haba dan kejatuhan tekanan untuk sistem $scCO_2$ dalam tiub lurus dan tiub heliks telah dianalisasi dengan menggunakan eksperimen dan simulasi. Semua pemboleh ubah proses dan geometri telah dioptimumkan dalam mendapatkan pemindahan haba yang lebih tinggi, dan kejatuhan tekanan yang rendah. Model simulasi telah dibina berdasarkan andaian bahawa aliran $scCO_2$ tidak boleh dimampat, turbulen dan tidak isotherma. Modal yang dibuat untuk tiub lurus telah disahkan dengan menggunakan keputusan eksperimen yang dikumpul daripada kesusasteraan. Manakala, untuk tuib heliks, kedua-dua simulasi dan eksperimen telah dijalankan bagi pelbagai pemboleh ubah: tekanan (7.0 MPa - 10 MPa), suhu (35 °C - 80 °C), kadar aliran (10 L/min - 35 L/min) dan diameter tiub (2.8 mm - 4.5 mm). Peratus perbezaan antara suhu dari model simulasi dan eksperimen adalah kurang daripada 10%. Ini membuktikan bahawa model simulasi yang telag dibuat adalah sah, dan boleh digunakan untuk menyelidik keunikan $scCO_2$. Kedua-dua keputusan eksperimen dan simulasi menunjukkan bahawa pemindahan haba mencapai nilai yang tertinggi bila tekanan dan suhu system $scCO_2$ berhampiran titik pseudo-kritikal. Apabila tekanan dalam system tersebut ditingkatkan melebihi tekanan kritikal, pemindahan haba berkurang, tetapi ia meningkat apabila kadar aliran dalam sistem ditambahkan. Manakala, pemindahan baha meningkat apabila diameter tuib yang lebih digunakan, berbanding dengan diameter tuib yang besar. Kejahunan tekanan pula berkurang apabila tekanan dalam sistem ditambahkan, tetapi ia meningkat bersama dengan kadar aliran. Selain itu, keputusan analisis sensitiviti Nusselt number dan kejatuhan tekanan menunjukkan pmebolhe ubah yang terbaik untuk $scCO_2$ dalam proses penyejukan. Tekanan sistem yang berdekatan dengan titik kritikal, diameter tuib yang kecil, dan kadar aliran yang tertinggi boleh mencapai pemindahan haba yang efisien dan juga kejatuhan tekanan yang rendah. Manakala, suhu sistem yang meningkat boleh menyebabkan pemindahan haba merosot. Gabungan pemboleh ubah ini boleh membantu mengurangkan kuasa pam yang dikaitkan dengan kejatuhan tekanan.

ABSTRACT

Supercritical carbon dioxide ($scCO_2$) is being used in many engineering applications because at supercritical stage, it has unique thermal properties with enhanced heat transfer and flow characteristics. Carbon dioxide (CO_2) at supercritical phase is being used recently in Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC&R) industries due to its special thermal properties of supercritical CO_2. However, the effects of some process and geometrical parameters on the thermal hydraulic performance of $scCO_2$ are not fully examined. Thus, the aim of this study is to develop single phase flow and heat transfer model and to investigate the effect of some process parameters (inlet pressure, inlet temperature, and inlet flow rate) and geometrical parameters (Tube inner diameter and tube shape) on the performance of $scCO_2$ cooling process. For the numerical investigation, two cases were considered: straight and helical tubes at various tube diameters. The model was developed based on the assumption that the $scCO_2$ flow is incompressible, turbulent and non-isothermal. The developed numerical model was validated using experimental data from open literature for the straight tube and by conducting experiments for the helical tube case. Both the simulation and experiment were performed at various input parameter range: pressure (7.0 MPa – 10 MPa), temperature (35 ºC – 80 ºC), flow rate (10 L/min – 35 L/min) and tube diameter (2.8 mm – 4.5 mm). The model validation results indicated that the average percentage error between the simulation and experimental results were less than 10%. This indicates that the developed model can be used to predict the performance of $scCO_2$ cooling process. Both the experimental and simulation results indicated that the heat transfer coefficient reaches peak value near the pseudo-critical point. Heat transfer coefficient decreased as inlet pressure increased beyond critical point but increased with increasing flow rate. Meanwhile, highest pressure drop value was recorded near the critical point. On the other hand, the smaller the inner tube diameter the higher the heat transfer coefficient will be. The pressure drop in a system decreased when the system inlet pressure is increased but increased with increasing flow rate. Besides, the sensitivity analysis results of Nusselt number and pressure drop indicate that the best input parameters in $scCO_2$ cooling. Inlet pressure with value near critical point, smaller tube *ID* and higher flow rate could achieve both enhanced heat transfer and low pressure drop at the same time. However, increasing inlet temperature could deteriorate heat transfer rate even though lower pressure drop was attained. These parameter combinations could help reducing the pumping power associated with pressure drop.

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