Ricardo Fernando Paes Tiecher

Modeling of New Commercial Refrigeration Systems Operating with Low-GWP Fluids

DISSERTAÇÃO DE MESTRADO

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Dissertação de Mestrado

Dissertation presented to the Programa de Pós-Graduação em Petróleo e Energia of the Departamento de Engenharia Mecânica do Centro Técnico Científico da PUC–Rio, as partial fulfillment of the requirements for the degree of Mestre em Engenharia Mecânica.

Advisor : Prof. José Alberto dos Reis Parise
Co–Advisor: Prof. Samuel Fortunato Yana Motta

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To uncle Sérgio, for being more than a father to me.

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Abstract

Tiecher, Ricardo Fernando Paes; Parise, José Alberto dos Reis; Motta, Samuel Yana. **Modeling of New Commercial Refrigeration Systems Operating with Low-GWP Fluids**. Rio de Janeiro, 2014. 219p. Dissertação de Mestrado — Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Comparison of new and conventional commercial refrigeration systems, operating with typical and alternative refrigerants, was performed. First, thermodynamic models for the pumped CO_2 and the CO_2 booster cycles were developed. The COP and the annual energy consumption of these novel designs were compared to those of the traditional direct expansion system in different geographic locations, to take into account year-round climate data. Refrigerant R404A, CO_2 and new low-GWP non-azeotropic blends were considered as working fluids in this analysis. Second, a component-based lumped parameter model to simulate the steady-state operation of a multi-compressor multi-evaporator direct expansion system was developed. The modeling effort considered a multizone approach for the tube-and-fin heat exchangers, as well as addressing enhanced internal surfaces and different fin patterns. Predicted results were compared with experimental data, and a life cycle climate performance (LCCP) analysis was performed to compare the environmental impact of new low-GWP refrigerants.

Keywords

commercial refrigeration. simulation. pumped CO_2. CO_2 booster. energy consumption. low-GWP fluids. environmental impact. LCCP.

Resumo

Tiecher, Ricardo Fernando Paes; Parise, José Alberto dos Reis; Motta, Samuel Yana. **Modelagem de Novos Sistemas de Refrigeração Comerciais Operando com Fluidos de Baixo GWP**. Rio de Janeiro, 2014. 219p. Dissertação de Mestrado — Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Configurações novas e tradicionais de sistemas de refrigeração comerciais foram comparadas considerando sua operação com fluidos refrigerantes alternativos. Primeiramente, desenvolveram-se modelos termodinâmicos para o ciclo transcrítico de dois estágios com refrigerante CO_2 (CO_2 booster) e para o sistema indireto com CO_2 bifásico operando como fluido secundário (pumped CO_2). Tais tecnologias foram, em seguida, comparadas com o ciclo de expansão direta (DX) por meio do COP e do consumo anual de energia. Nessa análise, R404A, CO_2, e misturas não-azeotrópicas de baixo GWP foram utilizados como fluidos refrigerantes. Em segundo lugar, desenvolveu-se modelo de parâmetros concentrados para simular a operação em regime permanente do sistema de expansão direta com múltiplos compressores e evaporadores. O método multizona foi utilizado na modelagem dos trocadores de calor tubo-e-aleta, com a consideração de diferentes tipos de aletas e superfícies internas para os tubos. Resultados da simulação foram comparados com dados experimentais e, em seguida, calculou-se o impacto ambiental do sistema operando com diferentes refrigerantes de baixo GWP, por meio da metodologia LCCP.

Palavras–chave

refrigeração comercial. simulação. sistema secundário. CO_2 transcrítico. consumo de energia. fluidos com baixo GWP. impacto ambiental. LCCP.

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Yes – I've learned from my mistakes, and I'm sure I could repeat them perfectly.

Jonathan Coe, *The Closed Circle.*

Nomenclature

a — parameter in Eqs. (B.16) to (B.18) , (B.46) to (B.48), and (B.70) to (B.72), Appendix A [kPa/°C]

a_0 — refrigerant-side heat transfer area per unit of air mass flow rate [m^2s/kg]

a^*_{min} — ratio between total air-side heat transfer area and total free-flow frontal area [-]

A — heat transfer area [m^2]

A_c —cross-sectional area [m^2]

A^*_f — total cross-sectional area of the fins obstructing air-flow [m^2]

A_{ff} — minimum free-flow frontal area [m^2]

A_{fin} — one microfin sectional area [m^2]

A_{rh} — refrigerant-side heat transfer area per unit of number of parallel circuits [m^2]

A_{sec} — total sectional area (considered when microfins are present) [m^2]

A^*_{tub} — "projected" area of tubes obstructing air flow [m^2]

b — parameter Eqs. (B.17) to (B.18), (B.47) to (B.48), and (B.71) to (B.72), Appendix A [kPa]

B — Bond number [-]

C — capacity rate [kW/°C]

c_1–c_{10} — parameters for the compressor polynomial equation [-]

c_p — specific heat at constant pressure [kJ/kg°C]

COP — coefficient of performance [-]

d — depth of the heat exchanger [m]

D — diameter of tubes [m]

D_c — fin collar outside diameter [m]

D_h — hydraulic diameter [m]

D^*_{rf} — adjusted inside (refrigerant-side) diameter of tubes for microfins [m]

E_{annual} — energy consumption per year [kWh/year]

E_h — enhancement factor for enhanced tube internal surfaces [-]

EER — energy efficiency ratio [BTU/Wh]

EOL — refrigerant loss at end-of-life [kg]

f — fraction of the heat exchanger [-]

F_P — fin pitch [fins/m]

Fr — Froude number [-]

G — mass flux [kg/m^{2}s]

G_a^* — adjusted air mass flux for wavy plate fins [kg/m^{2}s]

G_{rf}^* — adjusted refrigerant mass flux for microfins [kg/m^{2}s]

GWP_{fug} — warming potential of direct fugitive emissions during manufacture of equipment and fluids [kg CO_2/kg rf]

GWP_{emb} — warming potential of greenhouse gas emissions associated with equipment and fluids embodied energy [kg CO_2/kg rf]

GWP_{rf} — global warming potential of refrigerant relative to CO_2 [kg CO_2/kg rf]

GWP_{tot} — total global warming potential [kg CO_2/kg rf]

h — specific enthalpy [kJ/kg]

h_{fg} — latent heat difference [kJ/kg]

h'_{fg} — driving enthalpy difference, Section 5.2.1.2 [kJ/kg]

H — height of the heat exchanger [m]

j — Colburn factor [-]

k — thermal conductivity [kW/m°C]

l — length of the heat exchanger [m]

l_{exp} — length of each tube not covered by fins [m]

L_{annual} — refrigerant leakage rate per year [kg/year]

$LCCP$ — life cycle climate performance [kg CO_2]

m_{rf} — refrigerant mass or charge [kg]

$\dot{m}$ — mass flow rate [kg/s]

M — molecular weight [amu]

n — number of years of lifetime in LCCP calculation [years]

N_{circ} — number of equivalent, parallel refrigerant circuits [circuits]

N_f — number of fins [fins]

N_T — number of tubes in the direction of air-flow (horizontally) [tubes]

N_{tot} — total number of refrigerant tubes [tubes]

N_V — number of tubes in a row (vertically) [tubes]

NTU — number of transfer units [-]

Nu — Nusselt number [-]

P — pressure [kPa]

P_{init} — average pressure initialization value, Appendix A [kPa]

P_{red} — reduced pressure [-]

Pr — Prandtl number [-]

q — heat flux [kW/m^2]

$\dot{Q}$ — heat exchange rate [kW]

r — ratio of cooling loads [-]

R — thermal resistance [°C/kW]

R_p — pressure ratio [-]

Re — Reynolds number [-]

Re^* — superficial Reynolds number [-]

Rx — parameter considered in the determination of the heat transfer coefficient for two-phase refrigerant [-]

s — specific entropy [kJ/kg°C]

s_{ca} — Cavallini constant applied in the determination of the refrigerant two-phase heat transfer coefficient in the evaporator [-]

s_{cb} — convective boiling two-phase multiplier applied in the determination of the refrigerant two-phase heat transfer coefficient in the evaporator [-]

s_{nb} — nucleate boiling supression factor applied in the determination of the refrigerant two-phase heat transfer coefficient in the evaporator [-]

S_T — transversal pitch [m]

T — temperature [°C]

T_{gl} — temperature glide [°C]

$T^*_{v,ds}$ — bulk refrigerant temperature at the end of the single-phase vapor region [°C]

U — overall heat transfer coefficient [kW/m^2°C]

v — specific volume [m^3/kg]

V — velocity [m/s]

$\dot{V}$ — volumetric flow rate, displacement rate [m^3/s]

W — air humidity ratio [-]

$\dot{W}$ — power [kW]

W_T — horizontal distance between tubes (center-to-center) [m]

We — Webber number [-]

x — vapor quality [-]

x_{qw} — average vapor quality in mass basis [-]

Greek letters

α — film heat transfer coefficient [kW/m^2°C]

α_{rec} — recovery/recycling factor in the LCCP calculation [% rf]

α^*_{tp} — condensing refrigerant heat transfer coefficient before interpolation [kW/m^2°C]

β — indirect emission factor in LCCP calculation [kg CO_2/kWh]

β_1 — microfin angle [°]

β_2 — helix angle of microfins [°]

β_3 — microfin height [m]

β_4 — number of microfins [fins]

γ — percentage of refrigerant leak per year in the LCCP calculation [% rf/year]

γ_1, γ_2 — parameters for the calculation of the in-tube condensation heat transfer coefficient [-]

δ — fin thickness [m]

ΔP — pressure drop [kPa]

ΔP_{acc} — acceleration contibution to pressure drop [kPa]

ΔP_{frc} — friction contibution to pressure drop [kPa]

ΔT — temperature difference [°C]

ϵ — roughness [m]

ε — effectiveness [-]

ζ — friction factor [-]

ζ_{sm} — smooth tubes friction factor [-]

η — efficiency [-]

η_d — fin efficiency [-]

θ — corrugation angle for wavy fin, louver angle for louvered fin [°]

κ_h — parameter for the calculation of the dry air-side heat transfer coefficient for a tube with lanced plate fins [-]

κ_s — parameter for the calculation of the dry air-side heat transfer coefficient for a tube with lanced plate fins [-]

λ_1–λ_8 — parameters for the calculation of the dry air-side heat transfer coefficient for a tube with flat, wavy, lanced or louvered plate fins [-]

μ — dynamic viscosity [kg/ms]

ξ_{dh}, ξ_{sp}, ξ_{ba} — parameters for the calculation of the in-tube condensation pressure drop, the refrigerant two-phase heat transfer coefficient in the evaporator [-]

ρ — density [kg/m^3]

σ — surface tension [N/m]

σ_a — ratio between free-flow frontal area and frontal area [-]

τ_1, τ_2 — parameters for the calculation of the smooth tubes friction factor [-]

ϕ_S, ϕ_{F1}, ϕ_{F2}, ϕ_y, ϕ_{Be} — parameters for the calculation of void fraction using the Premoli et al. model

ϕ_i, ϕ_{Cal}, ϕ_{KH} — parameters for the calculation of void fraction using the Hughmark model

φ — intensive property

Φ — void fraction [-]

Υ — parameter of the compressor polynomial equation

ψ — parameter for the calculation of the bulk refrigerant temperature at the end of the single-phase vapor region [-]

Ω — parameter for the calculation of the dry air-side heat transfer coefficient for a tube with louvered plate fins [-]

Symbols

$\Im$ — error, Appendix A [°C]

$\wp$ — tolerance, Appendix A [°C]

Subscripts

a — air, air-side, outside

amb — ambient

avg — average, mean

bub — bubble point

bv — bypass valve

$Booster$ — CO_2 Booster refrigeration system

cd — condenser

cf — counterflow

$cond$ — condensing

cp — compressor

$crit$ — critical

cv — control valve

dew — dew point

dhx — downstream heat exchanger

dl — discharge line

dry — dry portion of the evaporator

ds — desuperheating, desuperheated zone

DX — Direct Expansion refrigeration system

eq — equivalent

ev — evaporator

$evap$ — evaporating

fl — flat fin pattern

gc — gas cooler

hs — high stage

$Hugh$ — Hughmark model for void fraction calculation

in — inlet, entrance, entering

ind — individual (compressor or evaporator)

l — subcooled region, saturated liquid

lc — lanced fin pattern

liq — liquid phase

ll — liquid line

ls — low stage

lt — low temperature

lv — louvered fin pattern

LT — refrigeration system for low temperature application

m — moist air conditions

max — maximum

med — average, Appendix A

min — minimum

mt — medium temperature

MT — refrigeration system for medium temperature application

na — non-azeotropic refrigerant mixture (NARM)

out — outlet, exit, leaving

pf — pure fluid

pp — pump

$Prem$ — Premoli et al. model for void fraction calculation

$Pumped$ — Pumped CO_2 refrigeration system

rec — receiver

rf — refrigerant, refrigerant-side, inside

s — isentropic

sat — saturation

sc — subcooling, subcooled zone

sf — secondary fluid

sh — superheating, superheated zone

shx — suction heat exchanger

sl — suction line

tp — two-phase region

uhx — upstream heat exchanger

v — superheated region, saturated vapor

vap — vapor phase

vl — vapor line

vol — volumetric

wet — wetted portion of the evaporator

wv — wavy fin pattern

xd — expansion device

Superscript

$+$ — new or updated value