INNOSTORAGE – USE OF INNOVATIVE THERMAL ENERGY STORAGE FOR MARKED ENERGY SAVINGS AND SIGNIFICANT LOWERING CO$_2$ EMISSIONS

Beneficiaries:

UNIVERSITAT DE BARCELONA
Universitat de Lleida
UNIVERSITÉ DE LYON
Ben-Gurion University of the Negev

Partners:

THE UNIVERSITY OF AUCKLAND NEW ZEALAND Te Whare Wānanga o Tāmaki Makaurau
University of South Australia
AUBURN UNIVERSITY

D7.2 - Report on Staff Exchanges

	Name and Institution	Date
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Contents

1 Objectives

This secondment has two objectives, one is to continue with the relationship between Prof. Farid at the University of Auckland and Prof. Cabeza and Assoc. Prof. Fernández from the University of Lleida and Barcelona, respectively. The second objective is to work in two different review papers, one on the potential of using supercritical CO_2 as heat transfer fluid and as storage material in thermal energy storage (TES) applications and a second one on the use of electricity price as control parameter in climatisation systems.

2 Supercritical CO_2 ($scCO_2$) as heat transfer fluid in thermal energy storage applications

Supercritical carbon dioxide is a fluid state of carbon dioxide where it is held at or above its critical temperature and critical pressure. Carbon dioxide behaves as a supercritical fluid above its critical temperature (304.25 K) and critical pressure (72.9 atm or 7.39 MPa), expanding to fill its container like a gas but with a density like that of a liquid (Figure 1). When fluids and gases are heated above their critical temperature and compressed above their critical pressure they enter a supercritical phase where some properties, such as solvent power, can be dramatically changed.

Supercritical CO_2 is becoming an important commercial and industrial solvent due to its role in chemical extraction in addition to its low toxicity and environmental impact. The relatively low temperature of the process and the stability of CO_2 also allows most compounds to be extracted with little damage or denaturing. In addition, the solubility of many extracted compounds in CO_2 varies with pressure, permitting selective extractions.

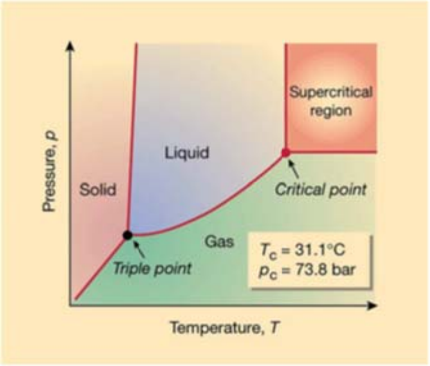

Figure 1. Supercritical CO2 p-T diagram[1]

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[1] X Zhang, S Heinonen, E Levänen. Applications of supercritical carbon dioxide in materials processing and synthesis. RSC Adv. 4 (2014) 61137-61152.

A short summary of supercritical CO_2 applications is presented here. Supercritical carbon dioxide ($scCO_2$) offers an acceptable combination of pressure and temperature to achieve supercritical conditions. $scCO_2$ is not a good solvent for most materials, which are $scCO_2$-phobic. However, both silicone and fluoro-products may be regarded as CO_2-philic and, therefore, potentially more soluble; such products are used in magnetic media production, one of the first applications of $scCO_2$ studied[2].

Another application investigated was supercritical extraction in petroleum refining and petrochemistry[3]. According to this publication, the advantages of carbon dioxide as solvent include: non-explosiveness and incombustibility; chemical inertness; absence of toxic wastes; sufficiently low critical parameters (pressure and temperature); low polarity; availability and low cost; high extraction rate due to high diffusing power.

The food industry is always looking for the best separation technology to obtain natural compounds of high purity, healthy products of excellent quality with several industrial applications. The conventional extraction process for those compounds has some limitations regarding the solvent toxicity, flammability and wastefulness. Supercritical carbon dioxide is an ideal supercritical fluid for the food processing industry because of its non-flammable, non-toxic, non-polluting and recoverable characteristics[4,5]. Examples of applications in the food industry are extraction of cholesterol and other lipids from egg yolk; milk fat fractioning; extraction of lipids and cholesterol from meat and meat products; from fish; extraction of natural colourings from several foodstuffs (such as carrots, leaf protein concentrates, sweet potatoes, tomato paste waste and tomato skin, and rape grape skin); extraction, refining and fractioning of oils and vegetable fats; extraction and fractioning of natural flavourings; extraction of antioxidants; decaffeinating of coffee and tea; extraction of hop; and de alcoholisation of drinks.

$scCO_2$ is also used in separation processes[6]. For example, Semenova and Ohya[7] studied the fractionation of $scCO_2$/ethanol and $scCO_2$/iso-octane mixtures using an asymmetric

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[2] K Johns. Supercritical fluids – a novel approach to magnetic media production? Tribology International 31 (1998) 485-490.

[3] MN Dadashev, GV Stepanov. Supercritical extraction in petroleum refining and petrochemistry. Chemistry and Technology of Fuels and Oils 36 (2000) 8-13.

[4] M Raventós, S Duarte, R Alarcón. Application and Possibilities of Supercritical CO2 Extraction in Food Processing Industry: An Overview. Food Sci Tech Int 8 (2002) 269-284.

[5] F Sahena, ISM Zaidul, S Jinap, AA Karim, KA Abbas, NAN Norulaini, AKM Omar. Application of supercritical CO2 in lipid extraction – A review. Journal of Food Engineering 95 (2009) 240–253.

[6] S Sarrade, C Guizard, GM Rios. New applications of supercritical fluids and supercritical fluids processes in separation. Separation and Purification Technology 32 (2003) 57-63.

[7] S.I. Semenova, H. Ohya, T. Higashijima, Y. Negishi. Separation of supercritical CO2 and ethanol mixtures with an asymmetric polyimide membrane. J. Membr. Sci. 74 (1992) 131-139.

Kapton membrane. The investigators concluded that CO_2 transfer across was predominantly by convection rather than diffusion. At approximately the same time, Hsu and Tan[8] proposed to use reverse osmosis membranes to fractionate water/ethanol mixtures in the presence of $scCO_2$. Under these conditions ethanol rejection is improved from 20 to 70%. The authors attributed the improved rejection to the formation of CO2 and ethanol clusters.

Song et al. [9] recognized in 2006 that even though CO_2 is a greenhouse gas, it is much more environmentally benign than many of the existing solvents used in industries. Environment-friendly and energy-efficient processes can be designed by using CO_2 for separation and chemical reaction and materials synthesis based on the unique physical or chemical properties of CO_2. For example, supercritical CO_2 can be used as either a solvent for separation or as a medium for chemical reaction, or as both a solvent and a reactant.

Extrusion processes have also used $scCO_2$, for example in polymer foaming[10]. $scCO_2$ is soluble in molten polymers and acts as plasticizer and the dissolution of $scCO_2$ in polymers leads to a decrease its viscosity. Therefore, extrusion processes would benefit from the use of $scCO_2$ since the rationale of extrusion processes is to formulate, texture and shape molten polymers by forcing them through a die. Applications using $scCO_2$ and extrusion are foodstuffs (i.e. breakfast cereals and snack foods); foaming of polymers (i.e. polystyrene and polycarbonate); composites (such as clay-polymer nanocomposites); biopolymers and pharmaceutical applications (dispersion to a molecular level of a pharmaceutical ingredient in a polymeric matrix).

Supercritical CO_2 is considered as a promising alternative for volatile organic solvents currently used in certain industrial processes and products, however, the poor solubilizing power of CO_2 towards polar substances remains a significant barrier to applications. Employing effective surfactants which generate stable dispersions and water/CO_2 microemulsions is accepted as one way to improve the physico-chemical properties of CO_2[11]. With compatible surfactants being developed, the applications of

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[8] J.H. Hsu, C.S. Tan. Separation of ethanol from aqueous solution by a method incorporating supercritical CO2 with reverse osmosis. J. Membr. Sci. 81 (1993) 273-285.

[9] C Song. Global challenges and strategies for control, conversion and utilization of CO2 for sustainable development involving energy, catalysis, adsorption and chemical processing. Catalysis Today 115 (2006) 2–32.

[10] M Sauceu, J Fages, A Common, C Nikitine, E Rodier. New challenges in polymer foaming: A review of extrusion processes assisted by supercritical carbon dioxide. Progress in Polymer Science 36 (2011) 749–766.

[11] J Eastoe, C Yan, A Mohamed. Microemulsions with CO2 as a solvent. Current Opinion in Colloid & Interface Science 17 (2012) 266–273.

CO_2 as a green, tunable, and easy to process solvent have received intensive interest. Studied applications in this field are synthesis of nanoparticles in w/c microemulsions and ionic liquid in $scCO_2$ microemulsions.

$scCO_2$ also has many unique properties and thus has great potential for advanced, green materials processing[1]. To investigate the potential of using supercritical CO_2 as heat transfer fluid and as storage material in thermal energy storage (TES) applications the literature was reviewed to summarize the known thermophysical properties of supercritical CO_2.

A table example of the review is presented in the Appendix of this report.

3 Electricity price as control strategy in thermal energy storage systems

There is an urgent need for more flexibility in the electric power system because the electric grid lacks a substantial storage capacity[12]. Nowadays, the balancing of the power system faces some problems. Firstly, it is hard to impossible to accurately predict the demand, the occurrence of incidents on the grid and the renewable energy output. Secondly, the load and renewable generating units are to a large extend inflexible, i.e., they do not react on changes in the power system. Instead of taking the conventional approach of investing in grid assets, which requires long lead times and massive investments, flexibility is increasingly being sought elsewhere, e.g. by dynamically controlling the DG units and loads. Storage is regarded as not yet economically viable, however, in the future, this may not be the case anymore.

Actually, the potentials of the end-users in the power management are relatively considerable compared with those of the power supply side. Instance, the end-users can contribute the major effort in peak load shaving instead of a huge capacity of grid energy storage (e.g., 7.5 MW/100 minutes[13].

Buildings can play a more active role in power balance regulation and grid operation[14]. With the benefits of thermal storage (e.g., building thermal masses, water/ice storage, and phase change materials), buildings actually have the considerable flexibility/elasticity in power demands (e.g., cooling load shifting, and peak power demand limiting). For the direct load management, the grid has the right to control the devices/systems of the end-users for reducing peak load and/or handling emergency situation. For the indirect load management,

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[12] Vardoorn et al. 2015 Control of storage elements in an islanded microgrid with voltage-based control of DG units and loads. International Journal of Electrical Power and Energy Systems 64:996-1006.

[13] Vazquez, et al. 2010 Energy storage systems for transport and grid applications. IEEE Transactions on Industrial Electronics 57(12):3881-3895.

[14] Wang et al. 2014 Building power demand response methods toward smart grid. HVAC and R Research 20(6):665-687.

the grid sends the price signals to in cent the end-users based on its expectation on the load reduction/shifting. Energy storage devices/ systems (batteries, flywheels, electric vehicles, thermal storage, etc.) in the grid can be employed to relieve the power imbalance by charging/discharging the power/energy.

Various energy storage systems have been used so far for peak load shifting. Some examples are hot water cylinders[15,16,17], residential refrigerators[18,19], ice banks[20], batteries[21], and thermal energy storage[22]. Between thermal energy storage, the use of the building mass[23,24] and the incorporation of PCM[25] have been studied.

4 Other activities

4.1. Seminar at The University of Auckland – Department of Chemical and Materials Engineering

On July 23rd, we had the chance to give a seminar to the students and staff of the Department of Chemical and Materials Engineering at UoA. The seminar was quite vivid with questions and interest from the audience.

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[15] Ericson 2009 Direct load control of residential water heaters. Energy Policy 37(9):3502-3512.

[16] Paull et al. 2010 A novel domestic electric water heater model for a multi-objective demand side management program. Electric Power Systems Research 80(12):1446-1451.

[17] Du and Lu 2011 Appliance commitment for household load scheduling. IEEE Transactions on Smart Grid 2(2):411-419.

[18] Niro et al. 2013 Large-scale control of domestic refrigerators for demand peak reduction in distribution systems. Electric Power Systems Research 100:34-42.

[19] Standler et al. 2009 Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices. Environmental Modelling & Software 24(2):285-295.

[20] Murphy et al. 2015 Comparison of control systems for the optimisation of ice storage in a dynamic real time electricity pricing environment. Applied Energy 149:392-403.

[21] Leadbetter and Swan 2012 Selection of battery technology to support grid-integrated renewable electricity. Journal of Power Sources 216, pp. 376-386.

[22] Ali et al. 2014 Combining the demand response of direct electric space heating and partial thermal storage using LP optimization. Electric Power Systems Research 106:160-167.

[23] Greensfeldera et al. 2011 An investigation of optimal control of passive building thermal storage with real time pricing. Journal of Building Performance Simulation 4(2):91-104.

[24] Braun et al. 2001 Evaluating the performance of building thermal mass control strategies. HVAC and R Research 7 (4), pp. 403-428.

[25] Zhang et al 2007 Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Building and Environment 42 (6), pp. 2197-2209.

4.2. Prof. Farid research group meeting

On July 22nd, we had the pleasure to attend the group meeting celebrated twice a year. In the meeting there was discussion of the research progress between students, and two presentations were given:

- Erwan Edi Saputro, PhD candidate: Application of PCM to compressed air energy storage (CAES)
- Kaveh Shahbaz, post-doctoral researcher: Application of deep eutectic solvents (DES) for purification of ester based PCM

4.3. Visit at Auckland University of Technology (AUT)

On July 21st, we had the chance to visit Prof. Adnan Al-Anbuky, director of the Centre for Sensor Network and Smart Environments (SeNSE) at AUT. His research is related to sensor networks, and potential collaboration has been identified.

5 Outcomes or future work

It is expected that these secondments will produce journal papers as a result of the collaboration with the different researchers. Particularly, the two reviews mentioned before should be submitted within two months after the secondment.

Moreover, we continue working in the ongoing project of testing fire behaviour of microencapsulated PCM produced by Prof. Farid team. Some testing are already done and we agreed in complete the testing with microcalorimeter assays and write a journal publication afterwards.

Nevertheless, the most important outcomes are all the future and possible links. Moreover, we have been working in a proposal for the next call of the Qatar Foundation.

6 Assessment

6.1 Assessment from Luisa F. Cabeza

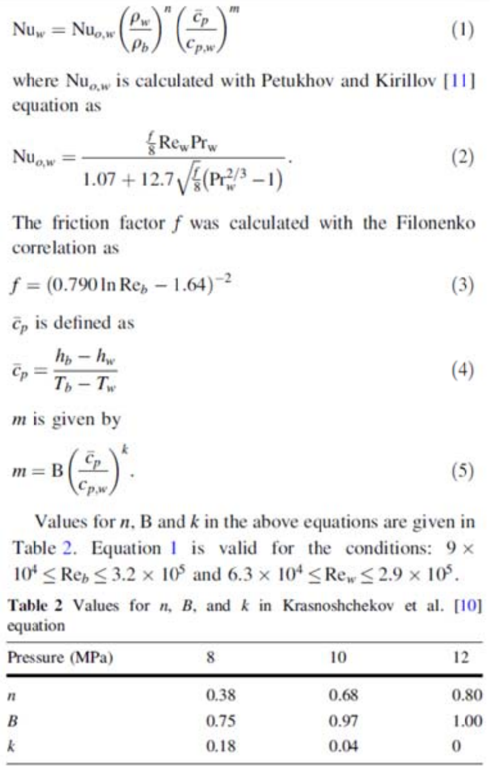
Being my forth visit to The University of Auckland and this time for a long period such as one month, this visit has been of high interest for me and my research team at the University of Lleida. I have had the opportunity to enhance the collaboration between both universities, but again being the visit together with Dr. Fernández from the University of Barcelona, the exchange has been even better to improve our collaboration.

6.2 Assessment from A. Inés Fernández

This has been a great opportunity for me to spend time with Prof. Farid an international recognized expert in phase change materials. I had the opportunity to complete the outcome from the previous visit of my PhD student Jessica Giró, and continue our ongoing work on testing the fire performance of mPCM developed at University of Auckland from renewable resources. The meetings and talks with PhD students and postdoc researchers were very fruitful and I wish I can contribute to their researches from my perspective as a materials scientist. The experience was excellent, as I had the possibility of knowing another way of working, trying to soak all possible skills experiencing research and knowledge sharing.

Appendix

Table 1. Horizontal pipe

<table>
<tr><th>Channel</th><th>Exp./ num.</th><th>Heat transfer model</th><th>Heat transfer equation</th><th>Reference</th></tr>
<tr><td rowspan="4">Horizontal circular tube
 </td><td>Exp</td><td>n.a.</td><td>$\mathrm{Nu}_b = \frac{(f/8)(\mathrm{Re}_b - 1000)\mathrm{Pr}_b}{1.07 + 12.7\sqrt{f/8}(\mathrm{Pr}_b^{2/3} - 1)}, \quad f = (0.79 \ln \mathrm{Re}_b - 1.64$</td><td>Petukhov et al. 1961[26]</td></tr>
<tr><td>Exp</td><td></td><td>

$$\mathrm{Nu}_w = \mathrm{Nu}_{o,w}\left(\frac{\rho_w}{\rho_b}\right)^n \left(\frac{\bar{c}_p}{c_{p,w}}\right)^m \tag{1}$$

where $\mathrm{Nu}_{o,w}$ is calculated with Petukhov and Kirillov [11] equation as

$$\mathrm{Nu}_{o,w} = \frac{\frac{f}{8}\mathrm{Re}_w \mathrm{Pr}_w}{1.07 + 12.7\sqrt{\frac{f}{8}}(\mathrm{Pr}_w^{2/3} - 1)}. \tag{2}$$

The friction factor f was calculated with the Filonenko correlation as

$$f = (0.790 \ln \mathrm{Re}_b - 1.64)^{-2} \tag{3}$$

$\bar{c}_p$ is defined as

$$\bar{c}_p = \frac{h_b - h_w}{T_b - T_w} \tag{4}$$

m is given by

$$m = \mathrm{B}\left(\frac{\bar{c}_p}{c_{p,w}}\right)^k. \tag{5}$$

Values for n, B and k in the above equations are given in Table 2. Equation 1 is valid for the conditions: $9 \times 10^4 \leq \mathrm{Re}_b \leq 3.2 \times 10^5$ and $6.3 \times 10^4 \leq \mathrm{Re}_w \leq 2.9 \times 10^5$.

Table 2 Values for n, B, and k in Krasnoshchekov et al. [10] equation

<table>
<tr><th>Pressure (MPa)</th><th>8</th><th>10</th><th>12</th></tr>
<tr><td>n</td><td>0.38</td><td>0.68</td><td>0.80</td></tr>
<tr><td>B</td><td>0.75</td><td>0.97</td><td>1.00</td></tr>
<tr><td>k</td><td>0.18</td><td>0.04</td><td>0</td></tr>
</table>
</td><td>Krasnoshchekov 1966[27]
Kasnoshchekov 1970[28]</td></tr>
<tr><td>exp</td><td>turbulent</td><td>$\mathrm{Nu}_b = \frac{(f/8)(\mathrm{Re}_b - 1000)\mathrm{Pr}_b}{1.07 + 12.7\sqrt{f/8}(\mathrm{Pr}_b^{2/3} - 1)}, \quad f = (0.79 \ln \mathrm{Re}_b - 1.6$</td><td>Gnielinski 1976[29]</td></tr>
<tr><td>exp</td><td>Turbulent flow</td><td>$\mathrm{Nu}_w = \mathrm{Nu}_w\left(\frac{\rho_w}{\rho_b}\right)^n \left(\frac{\overline{c_p}}{c_{p,w}}\right)^m, \quad \mathrm{Nu}_w = \frac{(f/8)\mathrm{Re}_w \mathrm{Pr}_w}{1.07 + 12.7\sqrt{f/8}(\mathrm{Pr}_w^{2/3} - 1)}$
$f = (0.79 \ln \mathrm{Re} - 1.64)^{-2}, \quad \overline{c_p} = \frac{h_b - h_w}{T_b - T_w}$
$m = 1.4$, $n = 0.15$ for $T_b/T_{pc} \leqslant 1$
m and n is given in table of Baskov et al. [15]' paper</td><td>Baskov 1977[30]</td></tr>
</table>

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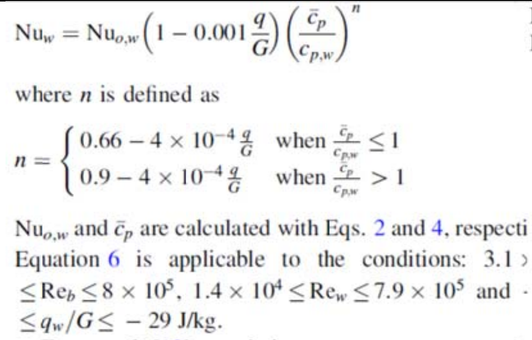
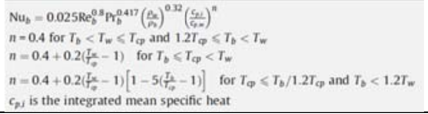
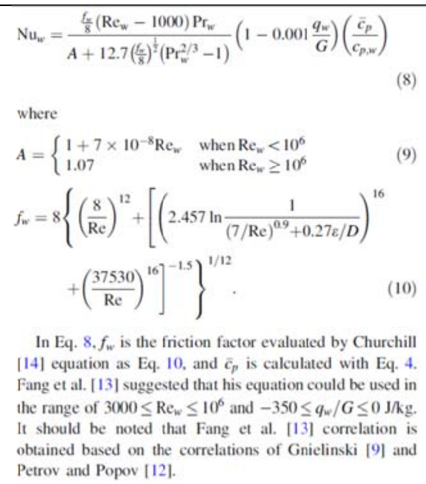
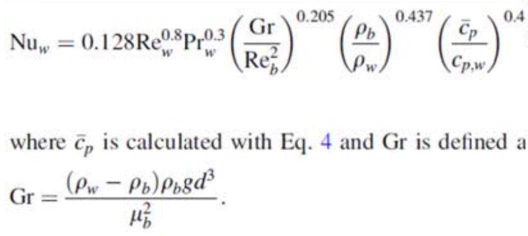
[26] B.S. Petukhov, E.A. Krasnoshchekov, V.S. Protopopov. An investigation of heat transfer to fluids flowing in pipes under supercritical conditions. ASME Int. Dev. Heat Transfer 3 (1961) 569–578

[27] E.A. Krasnoshchekov, V.S. Protopopov. Experimental study of heat exchange in carbon dioxide in the supercritical range at high temperature point. High Temp. 4 (1966) 375–382

[28] E.A. Krasonshchekov, I.V. Kuraeva, V.S. Protopopov. Local heat transfer of carbon dioxide at supercritical pressure under cooling conditions. Teplofizika Vysokikh Temp 5 (1970) 922–930

[29] V. Gnielinski. New equation for heat and mass transfer in turbulent pipe and channel flow. Int. Chem. Eng. 16 (1976) 359–368

[30] V.L. Baskov, I.V. Kuraeva, V.S. Protopopov. Heat transfer with the turbulent flow of a liquid at supercritical pressure in tubes under cooling conditions. Teplofizika Vysokikh Temp 15 (1977) 96–102

	Num		 $\mathrm{Nu}_w = \mathrm{Nu}_{o,w}\left(1-0.001\frac{q}{G}\right)\left(\frac{\bar{c}_p}{c_{p,w}}\right)^n$ where n is defined as $n = \begin{cases} 0.66 - 4\times10^{-4}\frac{q}{G} & \text{when } \frac{\bar{c}_p}{c_{p,w}} \le 1 \\ 0.9 - 4\times10^{-4}\frac{q}{G} & \text{when } \frac{\bar{c}_p}{c_{p,w}} > 1 \end{cases}$ $\mathrm{Nu}_{o,w}$ and $\bar{c}_p$ are calculated with Eqs. 2 and 4, respecti Equation 6 is applicable to the conditions: 3.1 $\le \mathrm{Re}_b \le 8\times10^5$, $1.4\times10^4 \le \mathrm{Re}_w \le 7.9\times10^5$ and $\le q_w/G \le -29$ J/kg. Eq 2 and 4 are those of Krasno…	Petrov and Popov 1985[31]
	exp	Forced convection	 $\mathrm{Nu}_b = 0.025\mathrm{Re}_b^{0.8}\mathrm{Pr}_b^{0.417}\left(\frac{\rho_w}{\rho_b}\right)^{0.32}\left(\frac{c_{p,i}}{c_{p,w}}\right)^n$ $n = 0.4$ for $T_b < T_w \leqslant T_{cp}$ and $1.2T_{cp} \leqslant T_b < T_w$ $n = 0.4 + 0.2\left(\frac{T_w}{T_{cp}} - 1\right)$ for $T_b \leqslant T_{cp} < T_w$ $n = 0.4 + 0.2\left(\frac{T_w}{T_{cp}} - 1\right)\left[1 - 5\left(\frac{T_b}{T_{cp}} - 1\right)\right]$ for $T_{cp} \leqslant T_b/1.2T_{cp}$ and $T_b < 1.2T_w$ $c_{p,i}$ is the integrated mean specific heat	Ghahar 1986[32]
	Num and Exp	buoyancy-free turbulent flow	Not a new one. Results compared to Gnielinski	Walisch 1996[33]
	Num	---	 $\mathrm{Nu}_w = \frac{\frac{f_w}{8}(\mathrm{Re}_w - 1000)\mathrm{Pr}_w}{A + 12.7\left(\frac{f_w}{8}\right)^{\frac{1}{2}}(\mathrm{Pr}_w^{2/3} - 1)}\left(1 - 0.001\frac{q_w}{G}\right)\left(\frac{\bar{c}_p}{c_{p,w}}\right) \quad (8)$ where $A = \begin{cases} 1 + 7\times10^{-8}\mathrm{Re}_w & \text{when } \mathrm{Re}_w < 10^6 \\ 1.07 & \text{when } \mathrm{Re}_w \ge 10^6 \end{cases} \quad (9)$ $f_w = 8\left\{\left(\frac{8}{\mathrm{Re}}\right)^{12} + \left[\left(2.457\ln\frac{1}{(7/\mathrm{Re})^{0.9} + 0.27\varepsilon/D}\right)^{16} + \left(\frac{37530}{\mathrm{Re}}\right)^{16}\right]^{-1.5}\right\}^{1/12}. \quad (10)$ In Eq. 8, f_w is the friction factor evaluated by Churchill [14] equation as Eq. 10, and $\bar{c}_p$ is calculated with Eq. 4. Fang et al. [13] suggested that his equation could be used in the range of $3000 \le \mathrm{Re}_w \le 10^6$ and $-350 \le q_w/G \le 0$ J/kg. It should be noted that Fang et al. [13] correlation is obtained based on the correlations of Gnielinski [9] and Petrov and Popov [12].	Fang 2001[34]
	Exp	Forced convection	 $\mathrm{Nu}_w = 0.128\mathrm{Re}_w^{0.8}\mathrm{Pr}_w^{0.3}\left(\frac{\mathrm{Gr}}{\mathrm{Re}_b^2}\right)^{0.205}\left(\frac{\rho_b}{\rho_w}\right)^{0.437}\left(\frac{\bar{c}_p}{c_{p,w}}\right)^{0.4}$ where $\bar{c}_p$ is calculated with Eq. 4 and Gr is defined a $\mathrm{Gr} = \frac{(\rho_w - \rho_b)\rho_b g d^3}{\mu_b^2}.$	Liao and Zhao 2002[35]

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[31] N.E. Petrov, V.N. Popov. Heat transfer and resistance of carbon being cooled in the supercritical region. Thermal Eng. 32 (1985) 131–134.

[32] A.J. Ghahar, A. Asadi. Improved forced convective heat-transfer correlations for liquids in the near-critical region. AIAA J. 24 (1986) 2030–2037.

[33] Walisch, T.; Muller, M.; Dorfler, W.; Trepp, Ch. The heat transfer to supercritical carbon dioxide in tubes with mixed convection. Process Technology Proceedings (1996), 12(High Pressure Chemical Engineering), 199-200.

[34] Fang, Xiande; Bullard, Clark W.; Hrnjak, Predrag S. Heat transfer and pressure drop of gas coolers. ASHRAE Transactions (2001), 107(1), 255-266.

[35] Liao, S. M.; Zhao, T. S. Measurements of heat transfer coefficients from supercritical carbon dioxide flowing in horizontal mini/micro channels. Journal of Heat Transfer (2002), 124(3), 413-416.

	Exp	Turbulent flow	$\mathbf{Nu}_b = 0.354\mathbf{Re}_b^{0.8}\mathbf{Pr}_b^{0.4}\left(\frac{\mathbf{Gr}_m}{\mathbf{Re}_b{}^{2.7}}\right)^{0.157}\left(\frac{\rho_w}{\rho_b}\right)^{1.297}\left(\frac{\bar{c}_p}{c_{p,b}}\right)^{0.296}$ for vertical upward flow $\mathbf{Nu}_b = 0.643\mathbf{Re}_b{}^{0.8}\mathbf{Pr}_b{}^{0.4}\left(\frac{\mathbf{Gr}_m}{\mathbf{Re}_b{}^{2.7}}\right)^{0.186}\left(\frac{\rho_w}{\rho_b}\right)^{2.154}\left(\frac{\bar{c}_p}{c_{p,b}}\right)^{0.751}$ for vertical downward flow $\mathbf{Nu}_b = 0.124\mathbf{Re}_b{}^{0.8}\mathbf{Pr}_b{}^{0.4}\left(\frac{\mathbf{Gr}}{\mathbf{Re}_b{}^{2.7}}\right)^{0.203}\left(\frac{\rho_w}{\rho_b}\right)^{0.842}\left(\frac{\bar{c}_p}{c_{p,b}}\right)^{0.384}$ for horizonta	Liao 2002[36]
	Exp. and num.	n.a.	$\mathrm{Nu} = \left(\frac{\mathrm{Nu}_w + \mathrm{Nu}_b}{2}\right)\frac{k_w}{k_b}$ (1 where Nu_w and Nu_b are calculated with Gnielinski (197 equation at T_w and T_b, respectively.	Pitla 2002[37]
	Exp.	---	$\mathrm{Nu}_b = 0.14\mathrm{Re}_b^{0.69}\mathrm{Pr}_b^{0.66}$ when $T_b/T_{pc} > 1$ (14) $\mathrm{Nu}_b = 0.013\mathrm{Re}_b\mathrm{Pr}_b^{-0.05}\left(\frac{\rho_{pc}}{\rho_b}\right)^{1.6}$ when $T_b/T_{pc} \leq 1.$ (15)	Yoon 2003[38]
	Exp.	---	$\mathrm{Nu}_f = \frac{\frac{f_f}{8}(\mathrm{Re}_b - 1000)\,\mathrm{Pr}}{1.07 + 12.7\sqrt{\frac{f_f}{8}}(\mathrm{Pr}^{2/3} - 1)}$ (16) where Prandtl number is defined as $\mathrm{Pr} = \begin{cases} c_{p_b}\mu_b/k_b & \text{when } c_{p_b} \geq \bar{c}_p \\ \bar{c}_p\mu_b/k_b & \text{when } c_{p_b} < \bar{c}_p \text{ and } \mu_b/k_b \geq \mu_f/k_f \\ \bar{c}_p\mu_f/k_f & \text{when } c_{p_b} < \bar{c}_p \text{ and } \mu_b/k_b < \mu_f/k_f \end{cases}$ (17)	Dang and Hihara 2004[39]
	Num.	---		Dang and Hihara 2004b[40]
	Exp.	---	$\mathrm{Nu}_b = \mathrm{Re}_b^{0.55}\mathrm{Pr}_b^{0.23}\left(\frac{c_{p,b}}{c_{p,w}}\right)^{0.15}$ when $T_b/T_{pc} > 1$ (18) $\mathrm{Nu}_b = \mathrm{Re}_b^{0.35}\mathrm{Pr}_b^{1.9}\left(\frac{\rho_b}{\rho_w}\right)^{-1.6}\left(\frac{c_{p,b}}{c_{p,w}}\right)^{-3.4}$ when $T_b/T_{pc} \leq 1.$ (19)	Son and Park 2006[41]
	Num	Non-adiabatic	Not a new one	Agrawal 2007[42]
	num	Flow convection	Not a new one	Zhang 2007[43]

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	Exp.	Turbulent	$$\mathrm{Nu}_b = 0.023\mathrm{Re}_b^{0.7}\mathrm{Pr}_b^{2.5}\left(\frac{c_{p,b}}{c_{p,w}}\right)^{-3.5} \quad \text{when } T_b/T_{pc} > 1 \qquad (20)$$ $$\mathrm{Nu}_b = 0.023\mathrm{Re}_b^{0.6}\mathrm{Pr}_b^{3.2}\left(\frac{\rho_b}{\rho_w}\right)^{3.7}\left(\frac{c_{p,b}}{c_{p,w}}\right)^{-4.6} \qquad (21)$$ when $T_b/T_{pc} \le 1$.	Oh and Son 2010[44]
	Exp (very similar to (101))	n.a.	None	Niu 2011[45]
	Exp (very similar to (23))	n.a.	Based on (58)	Zhang 2011[46]
	Numerical and experimental	Turbulent	Not a new one	Lin 2012[47]
	num	turbulent	Not a new one	Yang 2013[48]
	exp	Convection turbulent	Not a new one (results compared to Dittus-Boelter)	Tanimizu 2015[49]

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