Current and Future Applications of SCFs in Power Engineering and Specifics of Calculation Thermophysical Properties in the Critical Point with NIST REFPROP Software

I. Pioro, H. Xie, and M. Mahdi

University of Ontario Institute of Technology, Oshawa, Ontario, Canada
E-mail: Igor.Pioro@uoit.ca

1. Introduction

It is well-known that electricity generation and its consumption are the key factors for advances in industry, agriculture, technology, and the level of living. Currently, about 38% of the electricity in the world is generated at coal-fired power plants (PPs)[1], many of which use SuperCritical-Pressure (SCP) Rankine "steam"-turbine power cycle[2]. This is the largest application of SC Fluids (SCFs), i.e., SC Water (SCW) in power industry. SCP Rankine cycle has 2nd highest thermal efficiency in power industry up to 55% (gas-fired combined-cycle PPs have up to 62%). In spite of impressive thermal efficiency, coal-fired PPs are the largest emitters of CO_2 into atmosphere. Therefore, world is looking into using renewables (hydro, wind, solar, etc.) and nuclear PPs (NPPs). Unfortunately, all current NPPs have subcritical-pressure Rankine cycle with up to 38% thermal efficiency for all light- and heavy-water reactors (423 nuclear-power reactors from 441) and up to 42% - for CO_2-, Na-, and He-cooled reactors[3]. Therefore, new generation or Generation-IV reactors should be connected to SCP Rankine cycle or high-temperature combined cycles with He, N_2, and/or CO_2 SCP working fluids[4].

2. Current Applications of SCFs in Power Engineering

In addition to the mentioned above application of SCW in the Rankine power cycle at coal-fired PPs, currently, we have 2 small nuclear-power reactors (100 MW_{el} each) in China, which cooled with He at the pressure: P=7 MPa, and within the range of temperatures: T=250-750°C (He critical parameters: P_{cr}=0.2283 MPa & T_{cr}=-267.95°C and pseudocritical T_{pc}=-248.64°C at P=7 MPa). Therefore, from the thermodynamic point of view He as the reactor coolant at these operating conditions is SCF. However, He thermophysical-properties behavior is similar to that of compressed gas, because He operating conditions are far away from the pseudocritical region, where all thermophysical properties undergo quite significant variations.

Also, currently, SCW Reactors (SCWRs) are under development in the world as one of the six Generation-IV concepts, and major thermalhydraulics experiments are performed in SCW[5,6] (P_{cr}=22.064 MPa & T_{cr}=373.95°C). However, due to high critical parameters of water complimentary experiments are performed in modelling SCFs such as CO_2[7] (P_{cr}=7.377 MPa & T_{cr}=30.98°C) and R-134a (P_{cr}=4.059 MPa & T_{cr}=101.06°C) or R-12[7] (P_{cr}=4.136 MPa & T_{cr}=111.97°C) as modelling fluids. In addition, SC CO_2 and SC refrigerants can be used in air-conditioning and geothermal-PP cycles, respectively.

3. Future Applications of SCFs in Power Engineering

Six Generation-IV nuclear-power-reactor concepts[4] include: 1) Very High Temperature Reactor (VHTR), He-cooled; 2) Gas-cooled Fast Reactor (GFR), He-cooled; 3) Sodium-cooled Fast Reactor (SFR), liquid Na-cooled; 4) Lead-cooled Fast Reactor (LFR), liquid Pb- or Pb-Vi-cooled; 5) Molten Salt Reactor (MSR); and 6) SCWR. From all these Generation-IV reactors, He and SCW are SCFs. Moreover, He-cooled reactors might be connected to the direct Brayton He-turbine power cycle or indirect combined cycles with the Brayton (N_2-He; N_2; or SC CO_2 working fluids) and Rankine cycles (subcritical steam or SC CO_2 working fluids). SFR can be connected to the indirect subcritical-pressure-steam Rankine cycle (traditional cycle used currently in Russian BN-600 and BN-800 reactors) or to the indirect combined SC CO_2 cycle. LFR can be connected to an indirect SCP Rankine cycle. MSR can be connected to the abovementioned indirect combined cycles similar to those of He-cooled reactors, and SCWR – to direct or indirect SCP Rankine cycle.

4. Deficiencies of NIST REFPROP Thermophysical-Properties Program

Table 1 lists values of thermophysical properties in the critical point of water for two vales of temperature increment: 0.01°C and 0.002°C. Analysis of the data in Table 1 shows that at the temperature interval of 0.002°C in the critical point (i.e., at P_{cr}=22.064 MPa and T_{cr}=373.946°C), the Program provides unusually high (actually, almost infinite) peak values for thermal conductivity (k), specific heat (c_p) (see Fig. 1), dynamic viscosity (μ), kinematic viscosity (ν), Prandtl number, and volumetric expansivity (β).

Table 1. Values of thermophysical properties in critical point of water (based on NIST REFPROP[9]).

Property (max / peak value)	**Value at T_{cr}**	
	373.95°C (ΔT=0.01°C)	**373.946°C (ΔT=0.002°C)**
k, W/m K	1.34	**454.3**
c_p, kJ/kg K	$3.86\cdot10^{3}$	**$2.42\cdot10^{9}$**
μ, μPa s	39.06	**66.34**
ν, cm²/s	$1.36\cdot10^{-3}$	$2.06\cdot10^{-3}$
Pr	112.58	**$3.53\cdot10^{5}$**
β, 1/K	6.74	**$4.5\cdot10^{6}$**

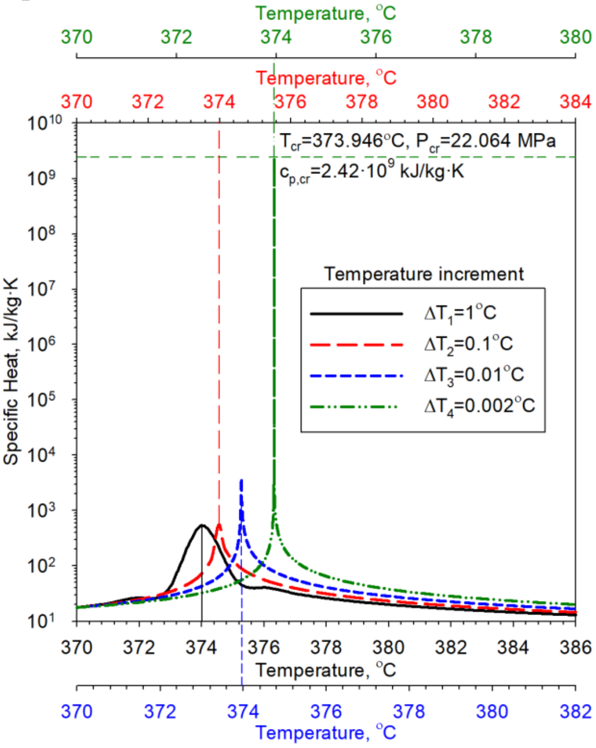

Figure 1. c_p vs. T: Water; critical region.

5. Conclusions

For tens of years, the NIST REFPROP program is used for calculations of various thermophysical properties of fluids, liquids, and gases / vapors, and is considered as the best one in the world. The latest Version 10.0 (2018) includes 147 pure fluids, 5 pseudo-pure fluids (e.g., air, mixtures of refrigerants, etc.), and mixtures with up to 20 components.

The most complicated thermophysical-properties calculations are within the critical region, where properties exhibit significant variations (see Fig. 1).

3. Current study shows that, possibly, the most reasonable temperature increment, especially, for properties with peak values is 0.002°C and a spline curve should be used to link calculated points (see Fig. 1). Also, the REFPROP[9], as the previous versions, exaggerates peak values (i.e., so-called, "optimistic" approach), which is not acceptable for many technical calculations (Table 1; Fig. 1). Therefore, it would be reasonable to use the latest experimental data for these peak values, and to adjust the corresponding equations / correlations used for calculating properties with peaks in critical point based on these experimental values.
4. Unfortunately, users / customers of the NIST REFPROP program have no rights and cannot change anything inside this program. Therefore, we have sent our findings to the NIST developers. Hopefully, the found deficiencies in the Program will be fixed in next version(s).

References

1. Pioro, I., Duffey, R., Kirillov, P., et al., 2020. Current Status of Reactors Deployment and SMRs Development in the World, ASME J. NERS, **6** (4), 24 pages: https://asmedigitalcollection.asme.org/nuclearengineering/article/6/4/044001/1085654/Current-Status-of-Reactors-Deployment-and-Small
2. Pioro, I.L. and Duffey, R.B., 2007. Heat Transfer and Hydraulic Resistance at SCPs in Power Engineering Applications, ASME Press, New York, NY, USA, 334 pages.
3. Pioro, I., Duffey, R., Kirillov, P., et al., 2021. Pros and Cons of Commercial Reactor Designs, Sect. 2: Chapter. Part 1. Current Status of Electricity Generation in the World and Selected Countries, pp. 263-287, in Encyclopedia of Nuclear Energy, 1st edition, Editor-in-Chief: E. Greenspan, Elsevier, UK, 3656 pages.
4. Handbook of Generation IV Nuclear Reactors, 2022. 2nd edition, Editor: I. Pioro, Elsevier – WP, Duxford, UK, 1140 pages.
5. Pioro, I., 2019. Current Status of Research on Heat Transfer in Forced Convection of Fluids at SCPs, NED, **354**, 14 pages.
6. Razumovskiy, V., Pis'mennyi, Eu., Sidawi, K., Pioro, I., et al., 2016. Experimental Heat Transfer in an Annular Channel and 3-Rod Bundle Cooled with Upward Flow of SCW, ASME J. NERS, **2** (1), 8 pages.
7. Saltanov, Eu., Pioro, I., Mann, D., et al., 2015. Study on Specifics of Forced-Convective Heat Transfer in SC Carbon Dioxide, ASME J. NERS, **1 (**1), 8 pages.
8. Richards, G., Harvel, G., Pioro, I., et al., 2013. Heat Transfer Profiles of a Vertical, Bare, 7-Element Bundle Cooled with SC R-12, NED, **264**, pp. 246-256.
9. NIST REFPROP, 2018. Ver. 10.0, E. Lemmon, I. Bell, M. Huber, and M. McLinden, National Institute of Standards and Technology, USA: https://www.nist.gov/srd/refprop.