Технічні науки

UDC 538.9:536.6

Fialko Nataliia
Doctor of Technical Sciences, Professor,
Corresponding Member of the NAS of Ukraine, Head of Department
Institute of Engineering Thermophysics of NAS of Ukraine
Фіалко Наталія Михайлівна
доктор технічних наук, професор,
член-кореспондент НАН України, завідувач відділу
Інститут технічної теплофізики НАН України

Meranova Nataliia
Candidate of Technical Sciences (PhD),
Senior Scientific Researcher, Leading Researcher
Institute of Engineering Thermophysics of NAS of Ukraine
Меранова Наталія Олегівна
кандидат технічних наук, старший науковий співробітник,
провідний науковий співробітник
Інститут технічної теплофізики НАН України

Sherenkovskiy Julii
Candidate of Technical Sciences (PhD),
Senior Scientific Researcher, Leading Researcher
Institute of Engineering Thermophysics of NAS of Ukraine
Шеренковський Юлій Владиславович
кандидат технічних наук, старший науковий співробітник,
провідний науковий співробітник
Інститут технічної теплофізики НАН України

Aleshko Sergiy

Candidate of Technical Sciences (PhD), Leading Researcher

Institute of Engineering Thermophysics of NAS of Ukraine

Альошко Сергій Олександрович

кандидат технічних наук, провідний науковий співробітник

Інститут технічної теплофізики НАН України

Khmil Dmytro

Junior Senior Researcher

Institute of Engineering Thermophysics of NAS of Ukraine

Хміль Дмитро Петрович

молодший науковий співробітник

Інститут технічної теплофізики НАН України

Sharaevsky Igor

Doctor of Technical Sciences, Associate Professor, Head of the Sector

Institute for Safety Problems of Nuclear Power Plants of NAS of Ukraine

Шараєвський Ігор Георгійович

доктор технічних наук, доцент, завідувач сектора

Інститут проблем безпеки АЕС НАН України

Zimin Leonid

Doctor of Technical Sciences, Senior Scientific Researcher, Leading Researcher

Institute for Safety Problems of Nuclear Power Plants of NAS of Ukraine

Зімін Леонід Борисович

доктор технічних наук, старший науковий співробітник,

провідний науковий співробітник

Інститут проблем безпеки АЕС НАН України

Vlasenko Tetiana
Candidate of Physico-Mathematical Sciences (PhD), Head of Department
Institute for Safety Problems of Nuclear Power Plants of NAS of Ukraine
Власенко Тетяна Станіславівна
кандидат фізико-математичних наук, завідувач відділу
Інститут проблем безпеки АЕС НАН України

Kutnyak Olha
Scientific Researcher of
Institute of Engineering Thermophysics of NAS of Ukraine
Кутняк Ольга Миколаївна
науковий співробітник
Інститут технічної теплофізики НАН України

Chekharovska Maryna
Senior Researcher
Institute of Engineering Thermophysics of NAS of Ukraine
Чехаровська Марина Ігорівна
старший науковий співробітник
Інститут технічної теплофізики НАН України

DYNAMIC VISCOSITY OF SUPERCRITICAL WATER FLOWING IN HEATED CHANNELS
ДИНАМІЧНА В'ЯЗКОСТЬ НАДКРИТИЧНОЇ ВОДИ ПРИ ТЕЧІЇ НАГРІВАНИХ КАНАЛАХ

Summary. *The data of the CFD analysis of the fields of dynamic viscosity of supercritical water in round channels for different values of the heat fluxq supplied to the wall are presented.*

Key words: *supercritical water, dynamic viscosity, CFD modeling, temperature fields, heat flux supplied.*

Анотація. *Представлені дані комп'ютерного моделювання полів динамічної в'язкості надкритичної води в круглих каналах при різних значеннях теплового потоку q, що підводиться до стінки.*

Ключові слова: *надкритична вода, динамічна в'язкість, CFD-моделювання, температурні поля, тепловий потік, що підводиться.*

Introduction. Further development of nuclear power plants is associated, as is known, with the use of power plants with new highly efficient nuclear reactors of the fourth generation [1]. Promising types of such reactors include, in particular, water-cooled supercritical pressure reactors. According to the international program Generation-IV (SCWR), industrial prototypes of these reactors are being developed.

One of the important features of supercritical water as a coolant in such reactors is that its thermophysical properties can change sharply and non-monotonically with temperature. Moreover, such a change is most significant in the region corresponding to the pseudo-critical transition "pseudo-fluid-pseudo-gas". The above predetermines the need to analyze the features of changes in the thermophysical properties of supercritical water in the working channels of the core of reactors with supercritical parameters. An effective method of such analysis is computer simulation, which is becoming more and more widely used for solving a number of problems in reactor thermal physics [2-14].

This work is devoted to the study, based on CFD modeling, of the regularities of change in the dynamic viscosity of supercritical water during its flow in vertical channels.

The purpose of the work and the formulation of research objectives. The purpose of this work is to perform a comparative analysis of the spatial distribution of the viscosity of supercritical water at different values of the density of the heat flux supplied to the channel wall during the upward flow. At the physical formulation of the problem under consideration, we solved the axisymmetric problem of mixed convection, which corresponds to the presence of forced and free motion of supercritical water (Fig. 1).

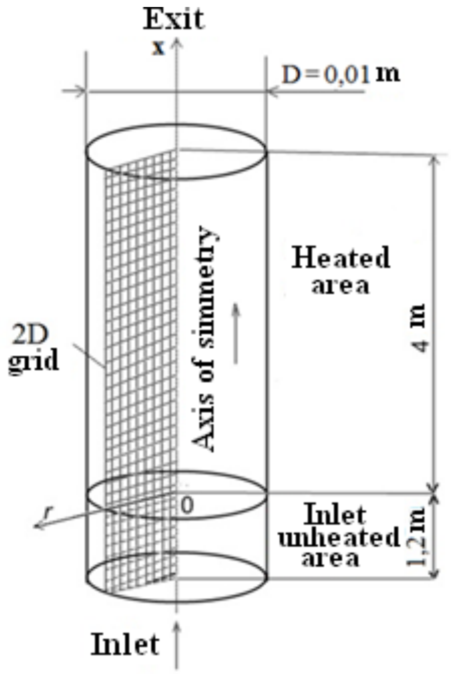


Fig. 1. To the problem statement

The spatial distributions of the viscosity of supercritical water in the channel were determined from the results of solving the nonlinear symmetric problem of mixed convection at flow in vertical smooth pipes.

For the purpose of hydrodynamic stabilization of the flow before entering the channel, the computational area was increased upstream due to the unheated initial part with a length l_{in}=1.2 m.

At the channel inlet, mass velocity G, temperature T_{in}, pressure P_{in} and the turbulence intensity Tu was taken unchanged. At the exit from the channel, "soft" boundary conditions were set. On the pipe wall, the values of the heat flux density q were assumed to be constant along its length.

In the course of the research, the features of the spatial distribution of the dynamic viscosity μ of supercritical water were considered.

Research methodology. Computer simulation using the FLUENT code was used as a research method. The physical properties of water, which appear in the mathematical model of the process under study, were determined using the NIST REFROP program [15]. The performed studies on the verification of turbulent transfer models substantiated the expediency of using the SST turbulence model.

The solution of the problem was carried out with non-uniform discretization of the computational domain containing 62400 cells. The size of the smallest step at the pipe wall was $1.5\cdot10^{-3}$ m. The value of y+ did not exceed 0.7. Numerical experiments were performed with the following initial data: d = 0.01 m; l_{in} = 1,2 m; L = 4,0m; T_{in}=323ºC; P_{in} =24,0 MPa; Tu =3%; G = 500kg/(m^{2}s); q = 239 kW/m^2 and 310 kW/m^2. The temperature dependence of the dynamic μ viscosity of supercritical water at P_{in} = 24,0MPa is shown in fig. 2.

As can be seen, in the temperature range under study, the dynamic viscosity of supercritical water decreases with an increase of temperatureby about a factor of three. In this case, the most significant decrease in the value of μ is observed in the area of the pseudocritical transition pseudoliquid - pseudogas (381.4 ºC).

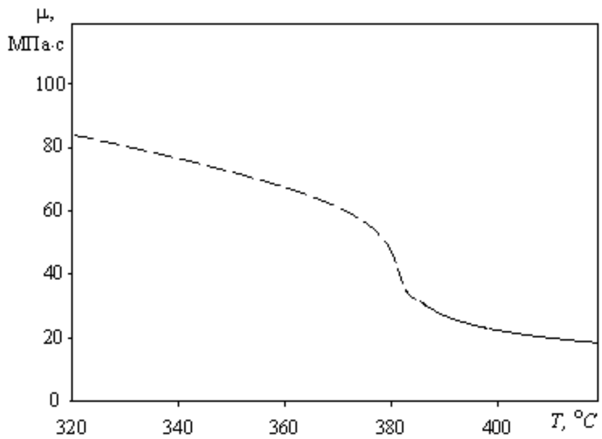


Fig. 2. Temperature dependence of dynamic viscosity μ of supercritical water at P_{in} = 24,0MPa

Research results and their analysis. The construction of the spatial distribution of the dynamic viscosity of supercritical water was carried out by temperature fields. The temperature fields are obtained as a result of solving the corresponding problem of mixed convection.

Figure 3 shows the temperature field in the channel for two values of the heat flux q supplied to the wall. (Here, for convenience of perception, the radial coordinate is increased by a factor of 400. The isotherms corresponding to the pseudocritical temperature T_{pc} are indicated in the figures by a thick line). As can be seen from fig. 3, the temperature fields of supercritical water in the channel are qualitatively similar to different values of the heat flux q. However, there are significant quantitative differences as well. For example, the T_{pc} isotherm of the pseudocritical transition, which separates the pseudofluid and pseudogas regions, is located noticeably closer to the channel exit section at q = 239 kW/m^2 (see the thick lines in the graph). The value of the x_{pc} coordinate corresponding to the inter section of the T_{pc} isotherm with the pipe axis is 3.08 m and 3.73 m for the heat flux supplied to the pipe wall q = 310 kW/m^2 and 239 kW/m^2. As for the temperature of supercritical water at the outlet of the channel, it is noticeably lower at q = 239 kW/m^2. It is also noteworthy that for both values of the heat flux q, a rather sharp increase in temperature is observed at the initial section of the pipe. Further downstream, this growth slows down (Fig. 3).

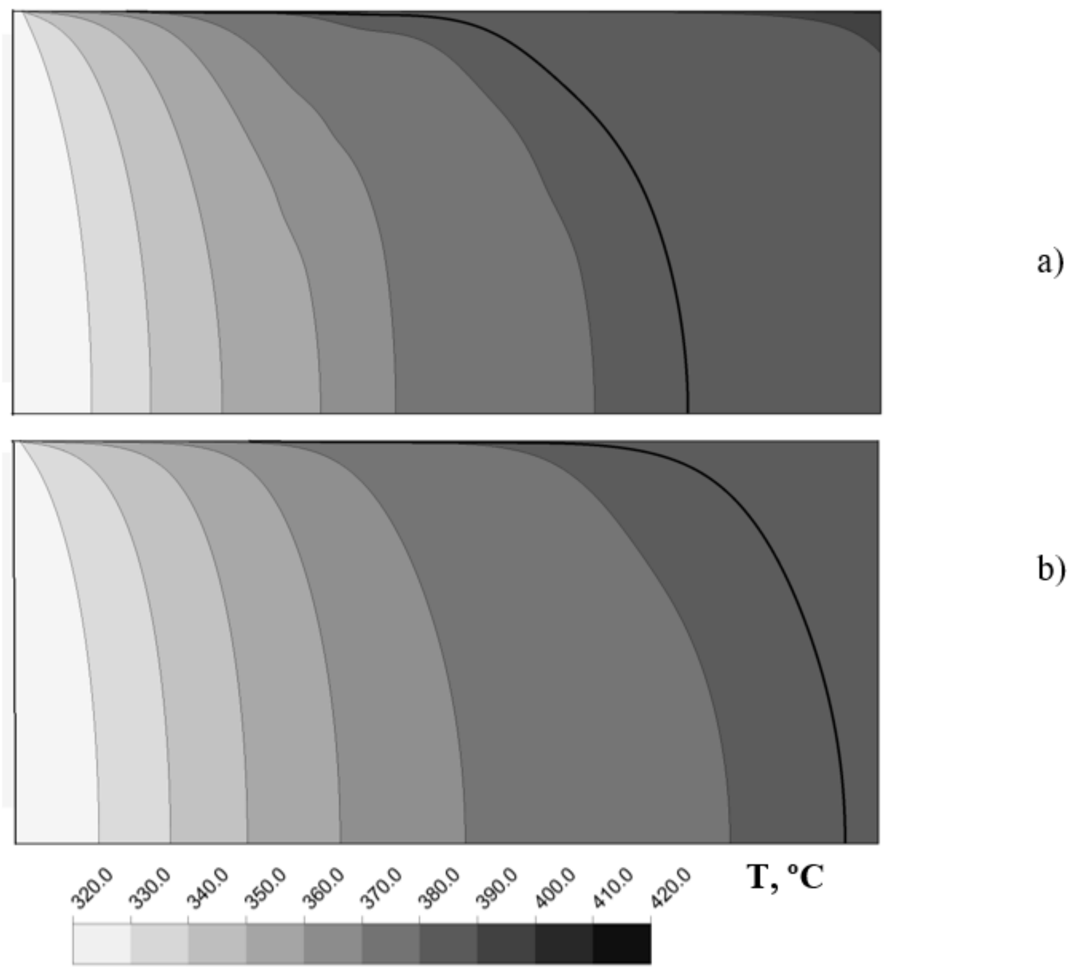
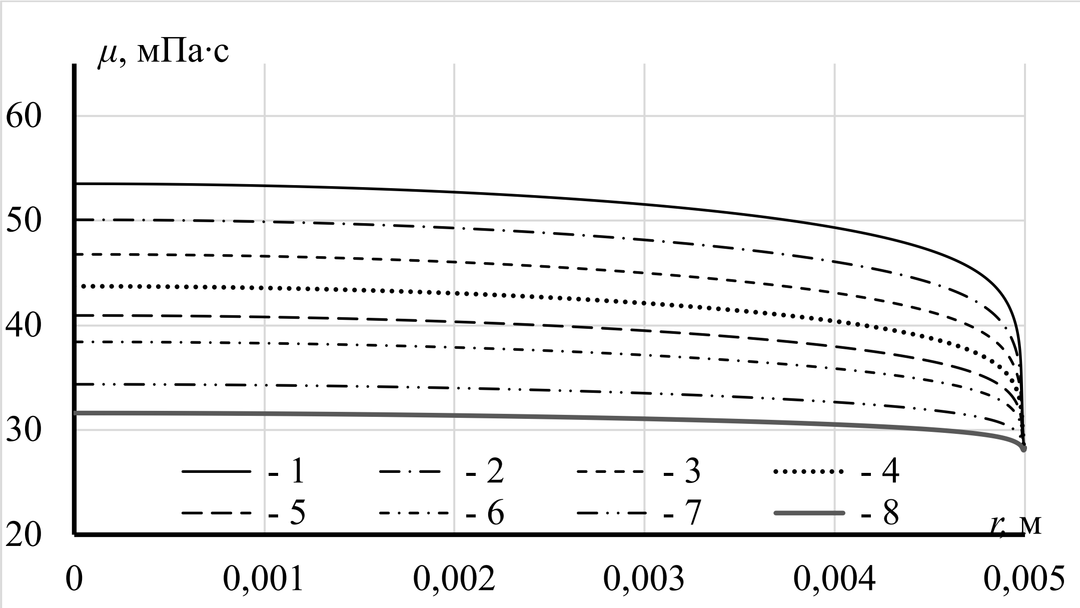
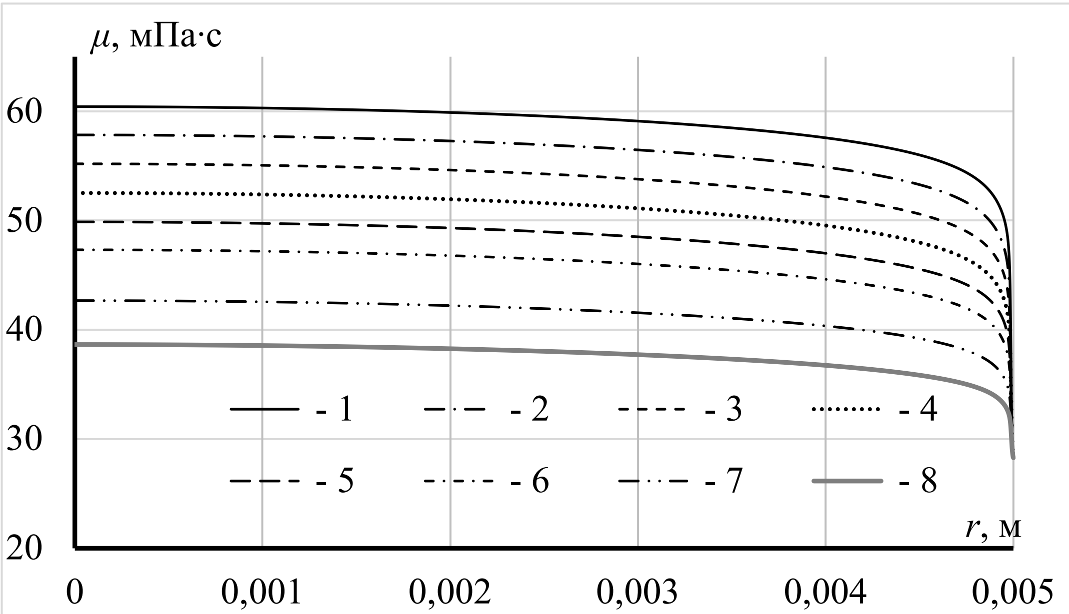


Fig. 3. Fields of dynamic viscosity μ of supercritical water in a channel for different values of the heat flux *q* supplied to the wall: a) *q* = 310 kW/m^2; b) *q* = 239kW/m^2

The distribution of dynamic viscosity μ along the radial coordinate *r* at different values of the coordinate x along the length of the pipe for two values of the heat flux *q* supplied to the wall is illustrated in Fig. 4



a)



b)

Fig. 4. Distribution of dynamic viscosity μ of supercritical water along the radial coordinate *r* at different values of the coordinate *x* along the length of the pipe for two values of the heat flux *q* supplied to the wall: a) q=310 kW/m^2; b) q=239 kW/m^2; 1 - x = 2.0 m; 2 - x = 2.2 m; 3 - x = 2.4 m; 4 - x = 2.6 m; 5 - x = 2.8 m; 6 – x = 3.0 m; 7- x = 3.4 m; 8 - x = 3.8 m

The data presented indicate that in fixed pipe cross sections, large values of μ occur on the pipe axis and decrease as one approaches its wall. This regularity is most clearly manifested in the central part of the pipe along the length. The described pattern of change along the pipe radius is typical for different values of the supplied heat flux q. In this case, a larger value of q (q = 310 kW/m^2) corresponds to noticeably larger differences in μ along the pipe radius in its initial and central part and somewhat smaller differences in the outlet part of the pipe.

Conclusions.

1. Studies have been carried out on a comparative analysis of the spatial distributions of the dynamic viscosity of supercritical water in channels for various values of the heat flux q supplied to the wall (q = 310 kW/m^2 and 239 kW/m^2).
2. The features of the temperature fields of supercritical water in the heated part of the channel, which determine the patterns of distribution of water viscosity for different values of q, have been established. It is shown that large values of q correspond to smaller sizes of the initial section of the channel, where supercritical water is in a pseudo-liquid state.
3. It is revealed that the dynamic viscosity μ of supercritical water decreases significantly with the flow. This decrease is the more significant for greater the value of the supplied heat flux q. It is shown that noticeably large differences in μ along the pipe radius in its initial and central part correspond to a higher value of q (q = 310 kW/m^2).

Referenses

1. Sharayevskyi I.G., Fialko N.M., Zimin L.B., Nosovskyi A.V., Vlasenko T.S., Sharayevskyi G.I. World Trends of Construction Development of water-cooled supercritical pressure reactor. Nuclear power and the environment. 2020. № 2(17). P. 3-15.
2. Fialko N.M., Pioro I.L., Maison N.V., Meranova N.O. Simulation of Flow and Heat Transfer in Bare Tubes at Supercritical Pressures. Industrial Heat Engineering. 2016. 38. № 3. P. 10-17.

3. Zvorykin A., Fialko N., Meranova N., Aleshko S., Maison N., Voitenko A., and Pioro I. Computer Simulation of Flow and Heat Transfer in Bare Tubes at Supercritical Parameters. Proceedings of the 24th International Conference on Nuclear Engineering (ICONE-24), June 26-30, 2016, Charlotte, NC, USA, Paper #60390, 12 p.
4. Fialko N.M., Pioro I.L., Maison N.V., Meranova N.O., Sharaevskiy I.G. Influence of the Mass Flux on the Characteristics of Flow and Heat Transfer in Bare Tubes at Supercritical Parameters. Industrial Heat Engineering. 2016. 38. № 4. P. 5-13.
5. Fialko N.M., Sherenkovskiy Ju.V., Meranova N.O., Aleshko S.A., Strizheus S.N., Voitenko A.Yu., Khmil D.P., Brusinskaya Ya.V., Ostapchuk T.S. Characteristics of Heat Transfer in Vertical Tubes at Supercritical Pressures. Problems of Ecology and Operation of Energy Facilitie. Institute of Industrial Ecology. Kyiv : IPC ALKON NAS of Ukraine. 2017. P. 130-133.
6. Zvorykin A., Fialko N., Sherenkovskiy J., Aleshko S., Meranova N., Hanzha M., Bashkir I., Stryzheus S., Voitenko A., and Pioro I. CFD Study on Specifics of Flow and Heat Transfer in Vertical Bare Tubes Cooled with Water at Supercritical Pressures. Proceedings of the 25th International Conference on Nuclear Engineering (ICONE-25), July 2-6 2017, Shanghai, China, Paper #66528, 13 p.
7. Fialko N.M., Pioro I.L., Prokopov V.G., Sherenkovskiy Ju.V., Meranova N.O., Aleshko S.A. CFD Modeling of Heat Transfer for Supercritical Water Flow in Vertical Bare Tubes. Industrial Heat Engineering. 2018. 40, № 1. P. 12-20.
8. Fialko N.M., Prokopov V.G., Sherenkovsk yJu. V., Meranova N.O., Aleshko S.A., Vlasenko T.S., Sharaevsky I.G., Zimin L.B., Strizheus S.N., Khmil D.P. Features of the Change in the Thermophysical Properties of

Supercritical Water during Flow in Round Heated Tubes. Scientific Bulletin of UNFU. 2018. 28, №3. P. 117-121.

9. Fialko N.M., Nosovskiy A.V., Sherenkovskiy Ju.V., Meranova N.O., Sharaevskiy I.G., Pioro I.L. Features of the Flow of Supercritical Water under Conditions of Mixed Convection. Industrial Heat Engineering. 2018. 40. № 3. P. 12-19.
10. Fialko N., Sherenkovskii Ju., Meranova N., Aleshko S., Vlasenko T. Thermophysical properties of supercritical water at an upward flow in vertical bare channels. International multidisciplinary conference "Science and technology of the present: priority directions of development of Ukraine and Poland." M. Volomin, October 19-20, 2018. P. 116-120. ISBN 978-9934-571-55-8.
11. Fialko N.M., Pioro I.L., Sherenkovskiy Ju.V., Maison N.V., Meranova N.O., Sharaevskyi I.G. Influence of Heat Flux on the Channel Wall and Water Pressure on the Characteristics of Flow and Heat Transfer in Bare Tubes at Supercritical Parameters. Industrial Heat Engineering. 2016. 38. № 5. P. 5-13.
12. Fialko N.M., Nosovskiy A.V., SherenkovskiyJu.V., Meranova N.O., Sharaevskyi I.G., Pioro I.L. CFD Analysis of Heat Transfer of Supercritical Water under Conditions of Mixed Convection. Industrial Heat Engineering. 2018. 40. №4. P. 5-12.
13. Zvorykina A., Khmil D., Fialko N., Pioro I., Stryzheus S. CFD Analysis of Supercritical-Water Flow and Heat Transfer in Vertical Bare Tube. 26th International Conference on Nuclear Engineering, (ICONE-26), October 24, 2018, V009T16A003; 14 p.
14. Fialko N.M., Nosovskiy A.V., Pioro I.L., Sherenkovskiy Ju.V., Meranova N.O., Aleshko S.A., Khmil D.P., Sharaevskyi I.G., Zimin L.B. Investigation of the Features of Heat Transfer of Supercritical Water in

Vertical Bare Tubes. Institute of Industrial Ecology. Kyiv : IPC ALKON NAS of Ukraine, 2019. P. 144-147.

15. National Institute of Standards and Technology, NIST Reference Fluid Thermodynamic and Transport Properties – REFPROP, NIST Standard Reference Database 23, Ver.8.0, Boulder, CO, U.S., Department of Commerce, 2007.