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Investigation on Laminar Flow and Heat Transfer of Helium–Xenon Gas Mixtures with Variable Properties

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Abstract: The space Brayton nuclear reactor system usually adopts the helium–xenon gas mixture (He–Xe) as the working fluid. The flow of He–Xe in the micro channel regenerator of the system is generally laminar. Since the properties of He–Xe are significantly different from those of common pure gases, the impact of this difference on the laminar flow and heat transfer needs to be evaluated. In present study, the numerical simulations of laminar convective heat transfer for helium, nitrogen and He–Xe are conducted by Ansys Fluent. Compared with simulation results, the applicability of existing laminar friction factor (f) and Nusselt number correlations is evaluated. By establishing the functions of property ratios with the temperature ratio and the mixing ratio, a new laminar f correlation for property-variable He–Xe is proposed. Results show that the calculation error of existing f correlations for He–Xe is obviously large, exceeding 13%. With the new f correlation, the predictions of laminar f for He–Xe are in good agreement with the simulation results in the fully developed region, and the calculation error is reduced to 3%.

Keywords: space nuclear reactor power; helium–xenon gas mixture; laminar flow; flow friction factor; numerical simulation

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1. Introduction

To meet the growing demand of space exploration, it is necessary to develop a more advanced and reliable space power system [1–3]. In comparison with common space power sources, such as chemical fuel cells or solar photovoltaic arrays, the high-power space nuclear reactor system can provide long-term, stable and efficient energy for nuclear-powered spacecrafts and planetary bases [4–8]. A gas-cooled reactor using the helium–xenon gas mixture (He–Xe) as coolant, combined with a direct Brayton cycle, can achieve a scheme for space nuclear power system with a lower specific mass and more compact design [9–12]. To reduce the aerodynamic loads of compressor and obtain an acceptable convective heat transfer coefficient, the He–Xe with molecular weight of 14.5–40.0 g/mol is generally recommended [13–16].

The high-temperature He–Xe regenerator is an important component of the space Brayton cycle system [17]. Due to the small size of heat exchange unit in the regenerator, the flow of He–Xe inside is usually laminar. Under the condition of constant properties, there exist theoretical solutions to the laminar friction factor (f) and Nusselt (Nu) number in the fully developed region in a smooth tube (fRe = 64, Nu = 48/11) [18]. However, when the wall temperature (T_w) differs greatly from the mainstream temperature (T_b), the cross-section properties in the tube will be different. Due to the influence of variable properties, the new law of the flow and heat transfer different from that of constant properties may appear [19–22]. Correlations derived from constant properties might not be applicable to the condition of variable properties [23,24]. The variation of properties for He–Xe is related to the mixing ratio, temperature, etc., and is different from that of common pure gases [25,26]. Additionally, the Prandtl (Pr) number of the recommended He–Xe with

14.5–40 g/mol will be as low as about 0.2, which is significantly lower than that of air, water and other conventional fluids (Pr > 0.70) [14,27]. In order to better evaluate the influence of property difference on the laminar flow and heat transfer, it is necessary to carry out in-depth research.

Our research is a traditional research topic about the gas flow and heat transfer with variable properties, and predecessors have conducted lots of studies on it. Maxwell et al. [28] numerically investigated the laminar convective heat transfer of air with variable properties in a rectangular channel, and the thermal entrance effect was analyzed. Taylor et al. [29] studied the gas laminar flow and heat transfer in the range of large temperature ratio ($0.35 < T_w/T_b < 7.35$) through experiments, obtaining a new f correlation by fitting experimental data. Additionally, Kays et al. [18] reviewed lots of researches on the gas laminar flow and heat transfer with variable properties, by which the modified f and Nu number correlations with temperature ratio were proposed. Herwig et al. [30] theoretically studied the laminar flow and heat transfer of gases under the small uniform heat flux; the expressions of f and Nu number in form of the property ratios were presented. By fitting the relevant experimental data, simplified correlations with the temperature ratio were also proposed by Herwig. However, the above studies mainly focused on single-component gases, not involving the gas mixtures with lower Pr numbers. Additionally, since most of the existing f and Nu number correlations for property-variable laminar flow are obtained by fitting experimental data, lacking theoretical basis, the application scope of the correlations is limited. In terms of laminar flow and heat transfer of He–Xe, Kurganov et al. [19] numerically compared the property-variable laminar f for monoatomic gases, diatomic gases, polyatomic gases and He–Xe, finding that the f of He–Xe was greater than that of other gases under the same conditions. Yang et al. [17] also investigated the He–Xe laminar flow and heat transfer in the high-temperature microchannel regenerator. However, the above two studies did not give the suitable f correlation for He–Xe. Therefore, the laminar flow and heat transfer characteristics of He–Xe with variable properties have yet to be revealed, and the suitable laminar f correlation for He–Xe still needs to be proposed.

In the present paper, the numerical simulations are firstly conducted to compare the difference in laminar flow and heat transfer between the He–Xe and conventional helium, nitrogen. The applicability of existing property-variable laminar f and Nu number correlations for He–Xe is evaluated. Thereafter, based on the theoretical expression of property-variable laminar flow, the quantitative analysis is conducted to explain the difference in laminar flow f between He–Xe and conventional gases. Additionally, by establishing the functions of property ratios with the temperature ratio and the gas mixing ratio, a new laminar f correlation for property-variable He–Xe is proposed. This new model can be used for the subsequent thermal hydraulics calculation and analysis of the micro-channel regenerator in space nuclear reactor systems.

2. Numerical Simulation Method

2.1. Calculation Model

For laminar flow, the numerical simulation based on the computational fluid dynamics (CFD) method is to directly solve the governing equations without introducing any assumptions and empirical coefficients. Under the premise of ensuring grid independence, numerical simulation results can be used as benchmark values. Therefore, the applicability of existing laminar f and Nu number correlations for He–Xe can be verified by comparing with the CFD simulation results.

As shown in Figure 1, the calculation model is a straight circular tube with a diameter (D) of 5.87 mm. The total length is 680.92 mm, of which the first part ($L_1 = 56D$) is adiabatic while the remaining ($L_2 = 60D$) is heated by uniform heat flux. In terms of the boundary conditions, the inlet is set to 'mass-flow-inlet', the outlet is set to 'pressure-out', and the wall surface adopts a non-slip boundary. The parameters of the specific calculation case are shown in Table 1. The setting of heat flux in Table 1 is to obtain different T_w/T_b, so as to better explore the influence of gas variable properties. The flow setting of different

gases is to keep the inlet Reynolds number consistent. It is noted that four helium–xenon gas mixtures of different molecular weights have been selected in previous studies [25,26], among which the He–Xe of 14.5 g/mol and 40.0 g/mol are commonly used as the working fluid in space reactor systems [6,13,15,31]. In the present paper, the He–Xe of 14.5, 28.3, 40.0 and 83.8 g/mol are also chosen.

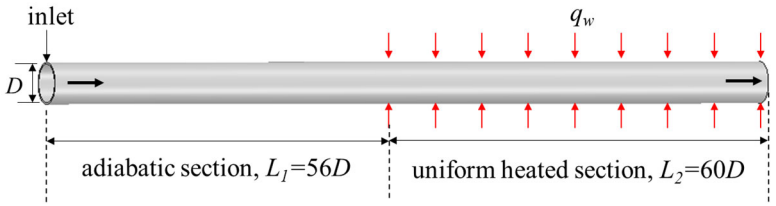

Figure 1. The calculation model of numerical simulation.

Table 1. The boundary conditions of numerical simulation.

Cases	Gaes	G/kg/m^2·s	q_w/W/m^2	T_i/K	P_o/MPa
1	Helium	6.47	15,000	300	0.2
2	Helium	6.47	25,000	300	0.2
3	Nitrogen	5.80	5000	300	0.2
4	Nitrogen	5.80	10,000	300	0.2
5	HeXe14.5	7.88	20,000	300	0.2
6	HeXe14.5	7.88	25,000	300	0.2
7	HeXe28.3	8.32	10,000	300	0.2
8	HeXe28.3	8.32	15,000	300	0.2
9	HeXe40.0	5.00	1000	300	0.2
10	HeXe40.0	8.37	9000	300	0.2
11	HeXe40.0	8.37	12,000	300	0.2
12	HeXe83.8	8.00	4000	300	0.2
13	HeXe83.8	8.00	6000	300	0.2

The properties of helium and nitrogen refer to the National Institute of Standards and Technology (NIST) database, which can be called by functions in ANSYS Fluent. Additionally, Tournier et al. [32] proposed semi-empirical correlations for calculating the properties of binary noble gases mixtures based on the Chapman–Enskog method. The accuracy of those property correlations was verified by comparing with experimental data [13–15]. In our previous papers [2,25,26], the variation in property for He–Xe was also analyzed in detail. Therefore, the properties of He–Xe continue using the semi-empirical correlations by Tournier in the present paper. Through user-defined functions (UDF), the correlation properties of He–Xe are imported into Ansys Fluent.

2.2. Grid Independence Test

As $Gr/Re^2 \ll 1$ is satisfied for all cases in Table 1, the gravitational effect is neglected and a two-dimensional calculation domain can be adopted [33]. Firstly, three meshes are used for the grid independence test (mesh 1: 40 × 3000 = 120,000, mesh 2: 60 × 4000 = 240,000, mesh 3: 80 × 6000 = 480,000). The test is carried out with case 9, and the calculation results are shown in Table 2.

Table 2. The grid independence test.

Axial Position, x	Parameter	Mesh 1	Mesh 2	Mesh 3
x = 0.45 m	T_w (K)	351.24	351.19	351.22
	T_b (K)	331.50	331.54	331.54
x = 0.60 m	T_w (K)	405.97	405.92	405.94
	T_b (K)	386.10	386.13	386.13

It can be calculated that the numerical deviation between mesh 2 and mesh 3 is less than 0.01%, thus the grid of mesh 2, as shown in Figure 2, can be considered sufficient. What is more, the laminar flow and heat transfer of constant properties is also simulated with mesh 2. It is found that the deviation of calculated f compared with 64/Re and the calculated Nu number compared with 48/11 in the fully developed region is less than 0.1%, which further verifies the rationality of mesh 2.

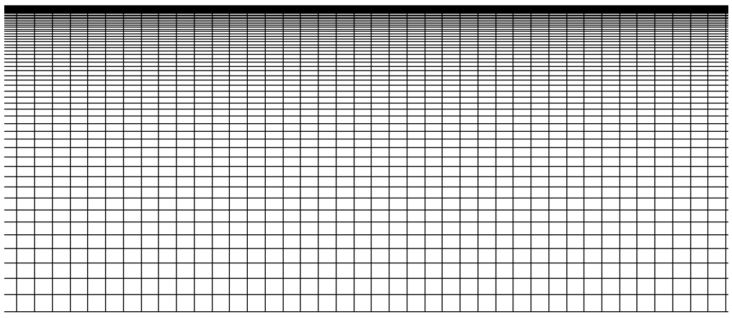

Figure 2. The grid of mesh 2.

3. Applicability of Existing Property-Variable Correlations

As shown in Table 3, the Nu number and f of laminar flow and heat transfer for three gases are calculated using Kays and Herwig correlations. The constant property correlations are also introduced for comparison. The applicability of existing variable property correlations to different gases are evaluated by comparing with CFD simulation results. The simulated local Nu number and f of gases are obtained by the following Equations (1) and (2), where λ denotes the cross-section average thermal conductivity, τ_w denotes the local wall shear and u_b denotes the average velocity.

$$\mathrm{Nu} = \frac{q_w}{T_w - T_b}\frac{D}{\lambda} \tag{1}$$

$$f = 8\tau_w/\rho u_b^2 \tag{2}$$

Table 3. Existing variable property correlations of laminar flow and heat transfer.

Name	Parameters	Correlations
Kays [18]	f	$\frac{f}{f_{cp}} = \left[\frac{T_w}{T_b}\right]^{1.0}$
	Nu	$\frac{Nu}{Nu_{cp}} = \left[\frac{T_w}{T_b}\right]^{0.0}$
Herwig [30]	f	$\frac{f}{f_{cp}} = \left[\frac{T_w}{T_b}\right]^{0.89}$
	Nu	$\frac{Nu}{Nu_{cp}} = \left[\frac{T_w}{T_b}\right]^{0.02}$

3.1. Applicability of Existing f Correlations

As shown in Figures 3 and 4, the laminar f of helium and nitrogen in the fully developed region of tube (x = 0.6 m) is calculated. As the x/D increases, the Re number decreases, and thus the laminar f increases. Compared with the CFD simulation results, calculations by the constant property correlation are obviously underestimated. The predictions by Kays and Herwig correlations for helium and nitrogen are found to be in good agreement with the simulation results. This is because the coefficients of Kays and Herwig correlations are determined mainly by fitting the experimental data of conventional gases, thus these correlations have good applicability to helium and nitrogen.

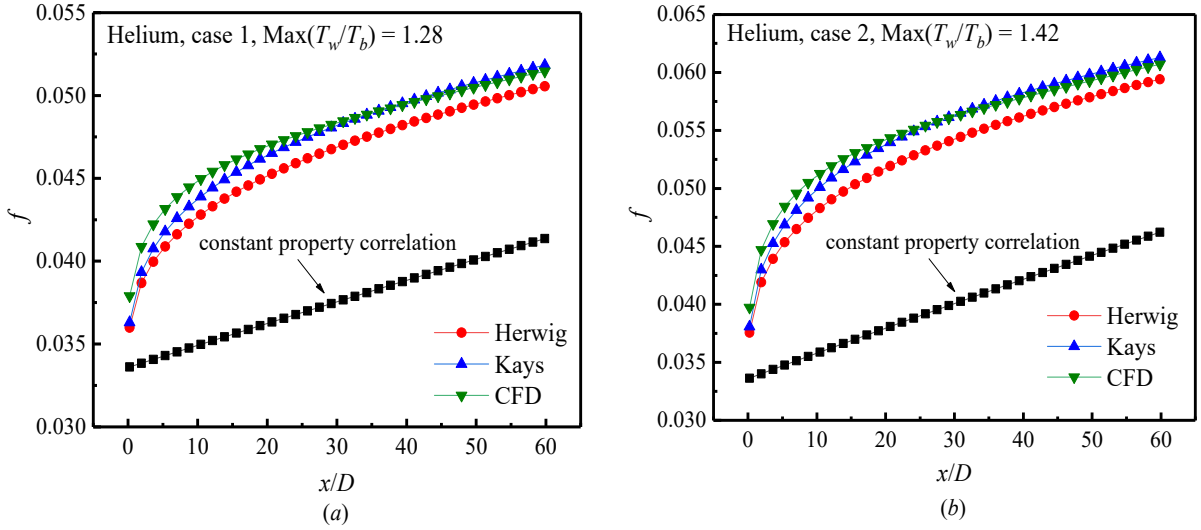

Figure 3. Calculations by existing f correlations for helium. (**a**) case 1; (**b**) case 2.

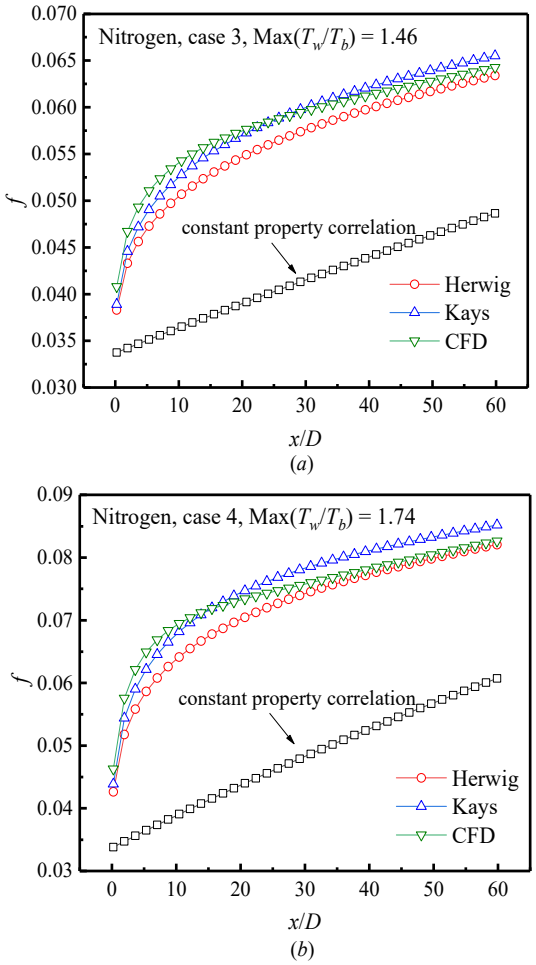

Figure 4. Calculations by existing f correlations for nitrogen. (**a**) case 3; (**b**) case 4.

As shown in Tables 4 and 5, the prediction errors of the three f correlations for helium and nitrogen are calculated based on case 1 and case 3, respectively. It can be found that the prediction error of the constant property correlation is close to 30% in the region of $\Delta x/D \geq 46.2$. Under the conditions of different T_w/T_b and Re number, the calculation errors of Herwig correlation for helium and nitrogen are less than 2.5% and that of Kays

correlation is less than 2.0%, which further indicates that the two correlations have good applicability to the f calculation for conventional helium and nitrogen.

Table 4. Calculation errors of helium by laminar flow f correlations.

$\Delta x/D$	T_w/T_b	Re	Error, f_{cp}	Error, f_{Herwig}	Error, f_{Kays}
46.2	1.27	1615	−20.9%	−2.2%	0.5%
47.9	1.27	1606	−20.8%	−2.1%	0.5%
49.6	1.27	1597	−20.6%	−2.0%	0.5%
51.3	1.26	1589	−20.4%	−2.0%	0.6%
53.0	1.26	1580	−20.3%	−1.9%	0.6%
54.7	1.26	1572	−20.1%	−1.9%	0.6%
56.4	1.26	1563	−20.0%	−1.8%	0.7%
58.1	1.26	1555	−19.8%	−1.8%	0.7%
59.8	1.25	1547	−19.6%	−1.7%	0.7%

Table 5. Calculation errors of nitrogen by laminar flow f correlations.

$\Delta x/D$	T_w/T_b	Re	Error, f_{cp}	Error, f_{Herwig}	Error, f_{Kays}
46.2	1.39	1408	−27.0%	−1.9%	1.7%
47.9	1.39	1395	−26.7%	−1.9%	1.7%
49.6	1.38	1383	−26.3%	−1.8%	1.8%
51.3	1.38	1371	−26.0%	−1.7%	1.8%
53.0	1.37	1360	−25.6%	−1.6%	1.9%
54.7	1.36	1348	−25.3%	−1.5%	1.9%
56.4	1.36	1337	−25.0%	−1.5%	1.9%
58.1	1.35	1326	−24.7%	−1.4%	1.9%
59.8	1.35	1316	−24.3%	−1.3%	2.0%

Correspondingly, the He–Xe with a molecular mass of 14.5 g/mol (HeXe14.5) is selected [13,15], and the laminar f of HeXe14.5 is calculated. As shown in Figure 5, the prediction error of constant property correlation is still large. It is worth noting that, unlike conventional gases, the predictions by Kays and Herwig correlations are significantly smaller than the CFD simulation results. As shown in Table 6, the prediction errors of Kays and Herwig correlations for HeXe14.5 are also presented based on case 6. It can be seen that the error of Herwig correlation is larger than 13% and that of Kays correlation also exceeds 11%. To explain the above deviations and propose a more applicable property-variable laminar f correlation for He–Xe, it is necessary to conduct in-depth studies.

Table 6. Calculation errors of HeXe14.5 by laminar f correlations with case 6.

$\Delta x/D$	T_w/T_b	Re	Error, f_{cp}	Error, f_{Herwig}	Error, f_{Kays}
46.2	1.21	1018	−26.8%	−13.1%	−11.2%
47.9	1.20	1003	−26.1%	−12.8%	−11.0%
49.6	1.20	988	−25.5%	−12.5%	−10.7%
51.3	1.19	974	−24.9%	−12.2%	−10.5%
53.0	1.18	960	−24.3%	−11.9%	−10.3%
54.7	1.18	947	−23.7%	−11.6%	−10.0%
56.4	1.17	934	−23.1%	−11.4%	−9.8%
58.1	1.17	922	−22.6%	−11.1%	−9.6%
59.8	1.16	910	−22.0%	−10.8%	−9.3%

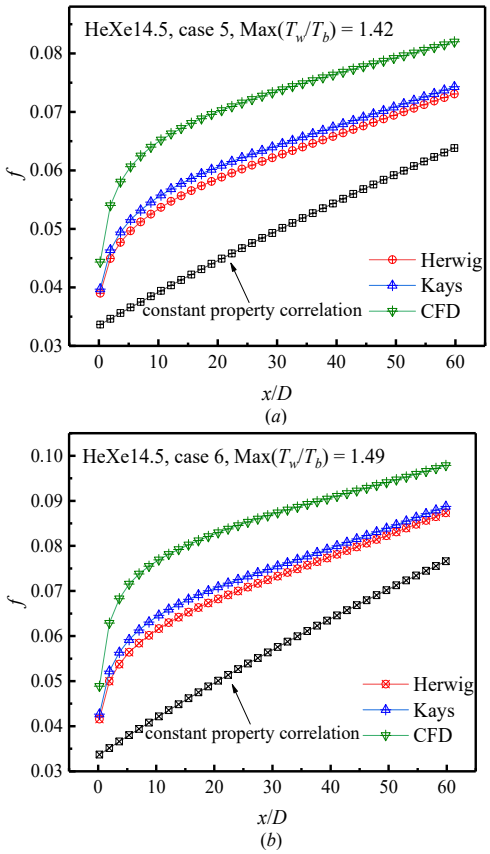

Figure 5. Calculations by existing f correlations for HeXe14.5. (**a**) case 5; (**b**) case 6.

3.2. Applicability of Existing Nu Number Correlations

As shown in Figures 6 and 7, the Nu numbers of property-variable laminar convective heat transfer for helium and nitrogen are calculated. At the beginning of heating, the thermal boundary layer is very thin and the thermal resistance is small, thus the surface convective heat transfer coefficient is large, resulting in the Nu number of gases being relatively high. As the thermal boundary layer becomes thicker, the heat transfer coefficient gradually decreases as the x/D increases, thus the Nu number decreases accordingly. When the gas flow reaches the fully developed state, the thickness of the boundary layer is stable, and the change of Nu number tends to be gentle. What is more, it is found that in the region of $\Delta x/D \geq 46.2$, all the calculations by the constant property correlation, Kays correlation and Herwig correlation are in good agreement with the CFD simulation results, indicating that the three existing correlations are suitable for Nu number calculation of laminar convective heat transfer for conventional helium and nitrogen in the fully developed region. Since the above three correlations do not consider the influence of the thermal entrance, there exists significant deviation between calculations by correlations and the CFD simulation results when $\Delta x/D \leq 46.2$. Additionally, predictions by the two property-variable correlations are very close to those by the constant property correlation, which illustrates that the variable property has a weak influence on the Nu number calculation for the laminar convection heat transfer. In order to further describe the calculation accuracy, the error of Nu number for the corresponding correlations is calculated. As shown in Tables 7 and 8, when $\Delta x/D \geq 46.2$, the calculation error of the three correlations is close, basically within 5.0%.

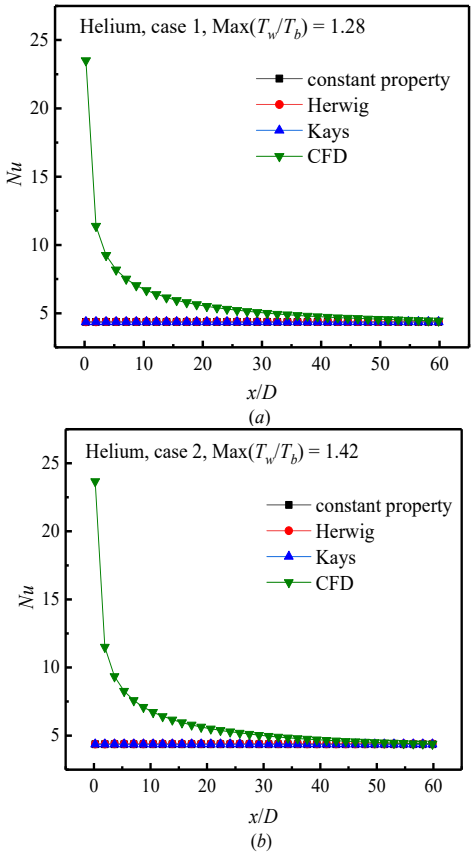

Figure 6. Calculations by existing Nu correlations for helium. (**a**) case 1; (**b**) case 2.

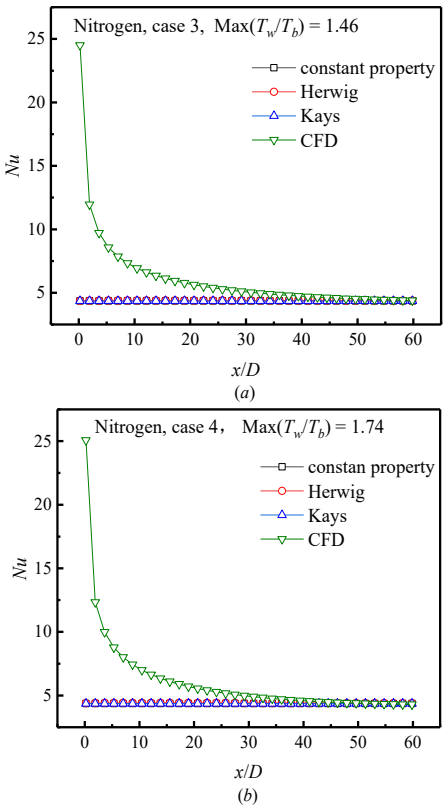

Figure 7. Calculations by existing Nu correlations for nitrogen. (**a**) case 3; (**b**) case 4.

Table 7. Calculation errors of helium by Nu number correlations with case 1.

$\Delta x/D$	T_w/T_b	Re	Error, Nu_{cp}	Error, Nu_{Herwig}	Error, Nu_{Kays}
46.2	1.27	1615	−5.6%	−3.6%	−5.6%
47.9	1.27	1606	−4.9%	−2.9%	−4.9%
49.6	1.27	1597	−4.4%	−2.4%	−4.4%
51.3	1.26	1589	−3.9%	−1.9%	−3.9%
53.0	1.26	1580	−3.5%	−1.4%	−3.5%
54.7	1.26	1572	−3.0%	−1.0%	−3.0%
56.4	1.26	1563	−2.6%	−0.5%	−2.6%
58.1	1.26	1555	−2.2%	−0.1%	−2.2%
59.8	1.25	1547	−1.9%	0.1%	−1.9%

Table 8. Calculation errors of nitrogen by Nu number correlations with case 3.

$\Delta x/D$	T_w/T_b	Re	Error, Nu_{cp}	Error, Nu_{Herwig}	Error, Nu_{Kays}
46.2	1.39	1408	−4.9%	−4.3%	−4.9%
47.9	1.39	1395	−4.1%	−3.5%	−4.1%
49.6	1.38	1383	−3.6%	−2.9%	−3.6%
51.3	1.38	1371	−3.0%	−2.4%	−3.0%
53.0	1.37	1360	−2.5%	−1.9%	−2.5%
54.7	1.36	1348	−2.0%	−1.4%	−2.0%
56.4	1.36	1337	−1.5%	−0.9%	−1.5%
58.1	1.35	1326	−1.1%	−0.5%	−1.1%
59.8	1.35	1316	−0.7%	−0.1%	−0.7%

Continuing to explore the applicability of the existing correlations to the Nu number calculation of He–Xe laminar convective heat transfer, as shown in Figure 8, it is found that the calculations by three correlations are still in good agreement with CFD simulation results in the fully developed region. As shown in Table 9, the calculation errors of Nu number correlations for HeXe14.5 are presented. Results show that the calculation errors of Herwig and Kays correlations are close to those of constant property correlation and are less than 3.0%. Therefore, in the subsequent thermal hydraulic design, the Nu number of He–Xe laminar convective heat transfer can still be calculated by existing correlations.

Table 9. Calculation errors of HeXe14.5 by Nu correlations with case 6.

$\Delta x/D$	T_w/T_b	Re	Error, Nu_{cp}	Error, Nu_{Herwig}	Error, Nu_{Kays}
46.2	1.21	1018	−2.4%	−2.1%	−2.4%
47.9	1.20	1003	−2.4%	−2.1%	−2.4%
49.6	1.20	988	−2.4%	−2.1%	−2.4%
51.3	1.19	974	−2.4%	−2.1%	−2.4%
53.0	1.18	960	−2.4%	−2.1%	−2.4%
54.7	1.18	947	−2.4%	−2.0%	−2.4%
56.4	1.17	934	−2.3%	−2.0%	−2.3%
58.1	1.17	922	−2.3%	−2.0%	−2.3%
59.8	1.16	910	−2.3%	−2.0%	−2.3%

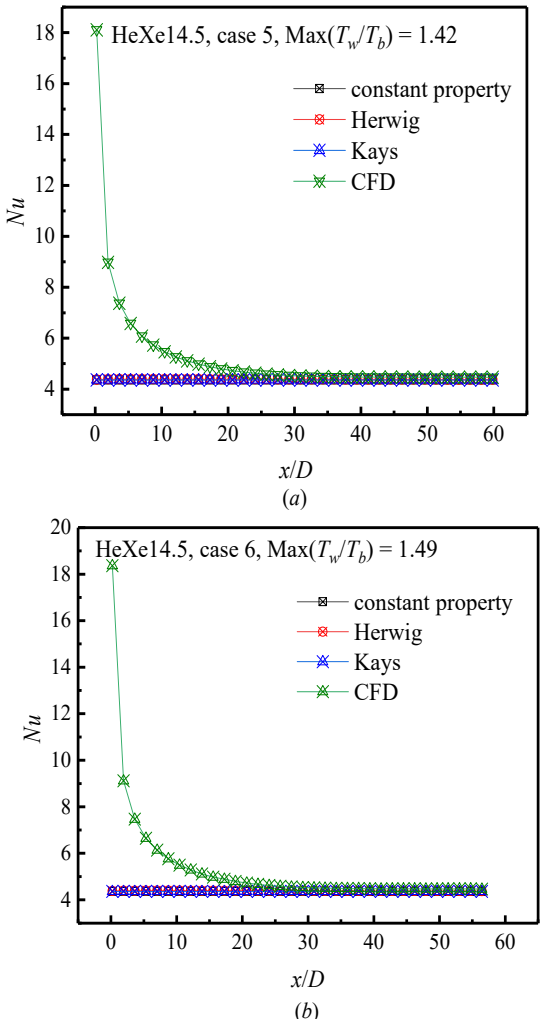

Figure 8. Calculations by existing Nu correlations for HeXe14.5. (**a**) case 5; (**b**) case 6.

4. Analysis and Discussion

4.1. Impact Factor Analysis

When the gas flows through the heated tube, the density, thermal conductivity and viscosity will change at the same time. It is difficult to directly theoretically derive the control equations of laminar flow and obtain the property-variable laminar f correlation. Herwig [30] used the Taylor expansion method to decompose the variable properties into the constant property term and linear difference term. By solving the zero-order and first-order equations respectively, a theoretical f correlation for the laminar flow with variable properties was derived, as shown in Equation (3).

$$\frac{f}{f_{cp}} = \left[\frac{\rho_w}{\rho_b}\right]^{(-0.364/\mathrm{Pr})} \left[\frac{\mu_w}{\mu_b}\right]^{0.545} \tag{3}$$

Based on Equation (3), the reason why the existing correlations underestimate the laminar f of He–Xe can be explained. It can be seen that the Equation (3) is composed of the property ratio term and the exponent item, thus these impact factors in Equation (3) can be quantificationally analyzed one by one. As shown in Figures 9 and 10, the variation of property ratio items with T_w/T_b is calculated.

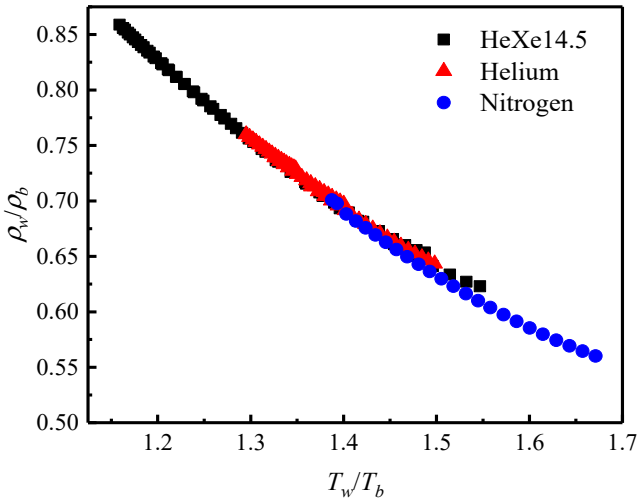

Figure 9. Variation of ρ_w/ρ_b with T_w/T_b for different gases.

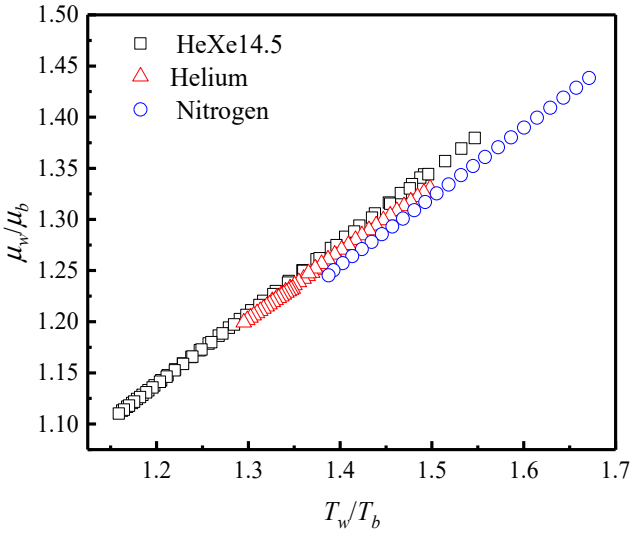

Figure 10. Variation of μ_w/μ_b with T_w/T_b for different gases.

It can be found that the variation trend of property ratios with T_w/T_b for different gases is basically similar. The gas laminar f is jointly affected by the density term and dynamic viscosity term. As shown in Table 10, the values of viscosity term for different gases are close under the same T_w/T_b. However, due to the difference in Pr numbers, the exponent of density term of HeXe14.5 is smaller than that of other gases, making the value of density term of HeXe14.5 is significantly larger. Therefore, under the same working conditions, the value of laminar flow f for He–Xe is larger than that of the conventional gases. Since Kays and Herwig correlations in Table 3 are proposed by fitting the experimental data of conventional gases, their predictions of laminar f for He–Xe are lower.

Table 10. Analysis of impact factors of property-variable laminar flow *f*.

T_w/T_b	Gas	Pr	Density Term			Viscosity Term			f/f_{cp}
			ρ_w/ρ_b	Exponent	Value	μ_w/μ_b	Exponent	Value	
1.50	HeXe14.5	0.30	0.649	−1.213	1.690	1.351	0.545	1.178	1.997
	Helium	0.67	0.649	−0.552	1.276	1.333	0.545	1.170	1.492
	Nitrogen	0.70	0.639	−0.520	1.268	1.323	0.545	1.165	1.477
1.40	HeXe14.5	0.30	0.692	−1.213	1.563	1.280	0.545	1.144	1.788
	Helium	0.67	0.692	−0.552	1.225	1.269	0.545	1.139	1.395
	Nitrogen	0.70	0.689	−0.520	1.214	1.256	0.545	1.132	1.374
1.30	HeXe14.5	0.30	0.756	−1.213	1.404	1.209	0.545	1.109	1.557
	Helium	0.67	0.756	−0.552	1.167	1.202	0.545	1.105	1.290

4.2. Modified with Temperature Ratio

Equation (3) is in the form of property ratios, which is difficult to be directly applied to engineering problems. Although Herwig subsequently tried to establish a simplified correlation with the temperature ratio correction, only the experimental data of air with a reference temperature of 20 °C was used in the actual formula fitting, which limited the application range of the simplified correlation. In terms of calculation accuracy, Herwig's simplified correlation is actually not good for He–Xe laminar f calculation. From Table 6, it can be seen that the Herwig's simplified laminar f correlation has a prediction error of more than 13% for He–Xe in the fully-developed region. Therefore, it is still necessary to propose a more applicable laminar f correlation for He–Xe. Since the property ratio of He–Xe show an obvious relationship with T_w/T_b, the function between the property ratio and the temperature ratio can be fitted to obtain a modified f correlation. As shown in Figure 11, the variation of density ratio with T_w/T_b for He–Xe under different cases is firstly calculated. It is found that the ρ_w/ρ_b of He–Xe is almost independent of the gas mixing ratios, but only varies with T_w/T_b. By numerically fitting the data points, the expression of ρ_w/ρ_b for He–Xe can be obtained:

$$\frac{\rho_w}{\rho_b} = \left(\frac{T_w}{T_b}\right)^{-1.063} \tag{4}$$

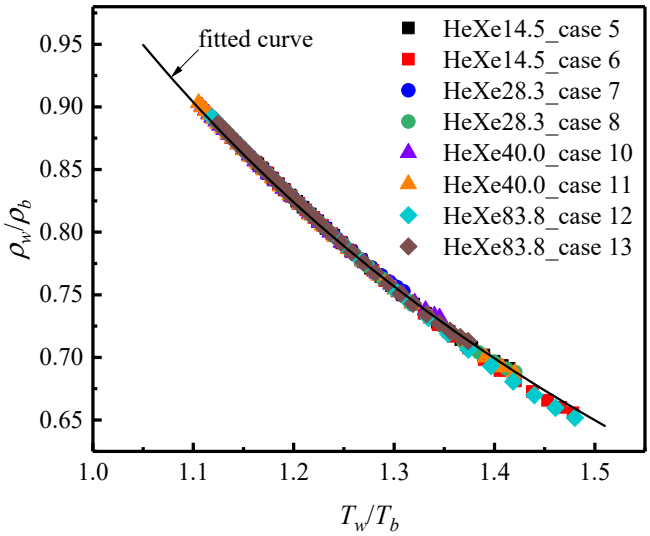

Figure 11. Variation of ρ_w/ρ_b with T_w/T_b for He–Xe.

As shown in Figure 12, the μ_w/μ_b of He–Xe is related to T_w/T_b, the mixing ratio x_1 and the heat flux q. When T_w/T_b is small, μ_w/μ_b is basically not affected by x_1 and q. However, when T_w/T_b is large, μ_w/μ_b changes slightly with x_1 and heat fluxes, which is mainly caused by the fact that the viscosity of He–Xe does not vary monotonously with the x_1 and temperature. Since the deviation caused by different heat fluxes is small in the range of $0 < x_1 < 0.30$ ($4.003 < M < 42.5$), the influence of x_1 and T_w/T_b on the μ_w/μ_b can be considered for simplification. By fitting the data points, the expression of μ_w/μ_b for He–Xe can be obtained as follows:

$$\frac{\mu_w}{\mu_b} = \left(\frac{T_w}{T_b}\right)^{(0.802-0.119(2.53e-3)^{x_1})} \tag{5}$$

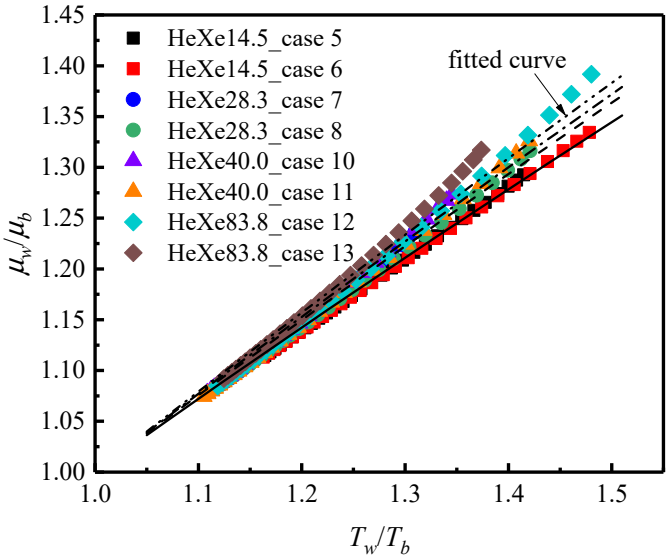

Figure 12. Variation of μ_w/μ_b with T_w/T_b for He–Xe.

Combining Equations (3)–(5), the modified f correlation with temperature ratio for property-variable He–Xe laminar flow is obtained:

$$\frac{f}{f_{cp}} = \left[\frac{T_w}{T_b}\right]^{(0.387/\mathrm{Pr}-0.0649(2.53e-3)^{x_1}+0.437)} \tag{6}$$

4.3. Error Analysis of Modified f Correlation

As shown in Figure 13, calculations by the new laminar f correlation are compared with the corresponding CFD simulation values of He–Xe. It is found that in the fully developed region, calculations by the new f correlation are in good agreement with the simulated results, which is obviously improved compared with the existing laminar f correlations. At the thermal entrance, the calculated value of new f correlation is slightly higher than simulation results; this is because the thermal entrance effect is not considered in the derivation of Equation (3). However, compared with Kays correlation, the prediction of Equation (6) proposed in the present paper is more conservative.

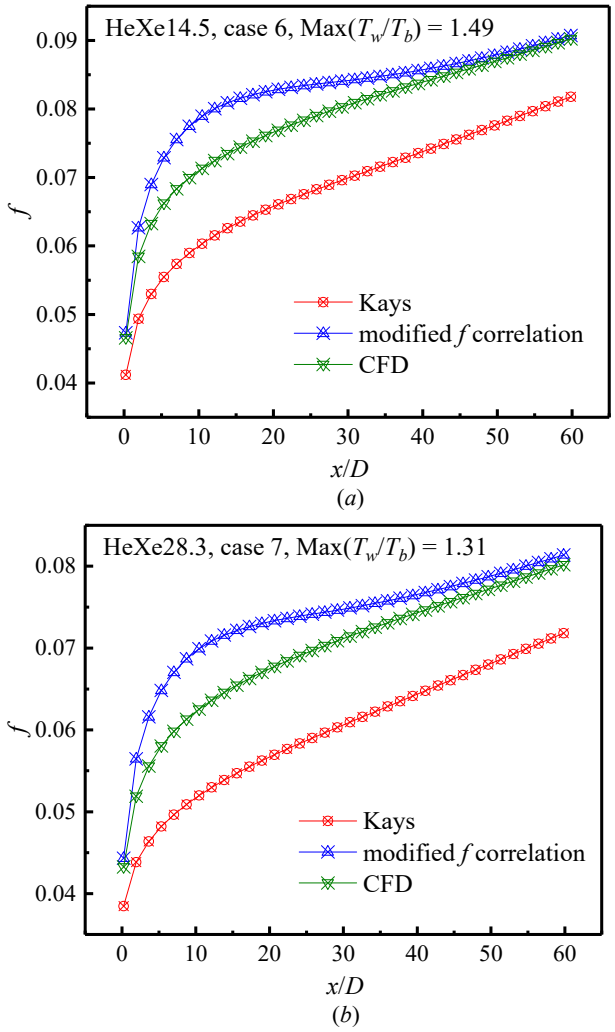

Figure 13. Applicability of the modified f correlation to He–Xe. (**a**) case 6; (**b**) case 7.

As shown in Tables 11 and 12, the calculation accuracy of the new f correlation for He–Xe laminar flow is presented. The calculation error is found to be less than 3% for $\Delta x/D \geq 46.2$, indicating that the new f correlation has good applicability to the laminar f calculation for property-variable He–Xe in the fully developed region.

Table 11. Calculation error of modified f correlation for HeXe14.5 with case 6.

$\Delta x/D$	T_w/T_b	Re	Error, f_{Kays}	Error, $f_{modified}$
46.2	1.21	1018	−11.2%	1.34%
47.9	1.20	1003	−11.0%	1.18%
49.6	1.20	988	−10.7%	1.05%
51.3	1.19	974	−10.5%	0.93%
53.0	1.18	960	−10.3%	0.83%
54.7	1.18	947	−10.0%	0.74%
56.4	1.17	934	−9.8%	0.67%
58.1	1.17	922	−9.6%	0.61%
59.8	1.16	910	−9.3%	0.55%

Table 12. Calculation error of modified f correlation for HeXe28.3 with case 7.

$\Delta x/D$	T_w/T_b	Re	Error, $f_{\mathbf{Kays}}$	Error, $f_{modified}$
46.2	1.15	1105	−12.4%	2.29%
47.9	1.15	1090	−12.2%	2.14%
49.6	1.14	1076	−11.9%	2.01%
51.3	1.14	1062	−11.6%	1.90%
53.0	1.13	1048	−11.4%	1.80%
54.7	1.13	1035	−11.1%	1.71%
56.4	1.13	1023	−10.9%	1.63%
58.1	1.12	1010	−10.7%	1.56%
59.8	1.12	998	−10.4%	1.50%

5. Conclusions

This paper numerically investigates the differences in laminar flow and heat transfer between He–Xe and conventional gases. The applicability of existing f and Nu number correlations to the property-variable He–Xe is evaluated. It is found that Kays and Herwig correlations have good prediction accuracy for conventional gases, but obviously underestimate the laminar f for He–Xe. The calculation error of Herwig correlation is more than 13% and that of Kays correlation also exceeds 11% in the fully developed region. Theoretical analysis shows that the Pr number is a key factor affecting laminar f with variable properties. By fitting the numerical simulation results, the functions of property ratios with T_w/T_b and x_1 for He–Xe are established, based on which a new f correlation modified with the temperature ratio is proposed. The results show that the calculation error of the new f correlation for He–Xe in the fully developed region is less than 3%, which is obviously improved compared with the existing correlations. The model proposed in the present paper can provide a reference for the subsequent thermal-hydraulic calculation of the He–Xe cooled nuclear reactor system.

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Nomenclature

D	diameter of tube (m)
f	friction factor
G	mass flux (kg/m^2·s)
M	molar weight (g/mol)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number
T	temperature
u	velocity
x	axial distance from inlet
x_1	molar fraction of xenon
Δx	axial distance from starting heated point

Greek letters	
μ	dynamic viscosity
λ	thermal conductivity
ρ	density
Subscripts	
b	average
i	inlet
o	outlet
w	wall
cp	constant property

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