Investigation of Deviations Between IFC-67 and IAPWS-IF97 Formulas in Reactor Core Power Calculations

Authors: The user has provided “刘奇洪” which is a Chinese name. This is not a paragraph with tags, LaTeX commands, or any of the structure described in the instructions. It’ s just a name.

According to the instructions: - I should translate from Simplified Chinese to English - I must preserve ALL ⋯paragraph wrapper tags EXACTLY - I must preserve ALL LaTeX commands and placeholders exactly - I must preserve ALL citation commands exactly as they appear - Maintain academic tone and formal scientific writing style - Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)

However, the input is just a name “刘奇洪”. This doesn’ t fit the expected format at all. There are no tags, no LaTeX, no citations. It’ s just a proper name.

For Chinese names, the standard academic translation is to use the pinyin romanization. “刘奇洪” would be “Liu Qihong” in English.

But the instructions say I must preserve tags. Since there are none, I should just provide the translation of the name. However, the instructions also say “Return ONLY the translated text for the given input” and “Keep one output paragraph per input paragraph; do not merge or split paragraphs.”

This is ambiguous. Is “刘奇洪” meant to be a complete paragraph that should be wrapped in a tag? Or is it just a fragment?

Given the strictness of the instructions about preserving tags, and the fact that the user might have intended this to be part of a larger document structure, I should consider that this might be a test or an incomplete input.

However, the most reasonable interpretation is that the user wants me to translate this Chinese name into English. In academic contexts, Chinese names are typically rendered in pinyin with the surname first: “Liu Qihong”.

But wait - the instructions say “PRESERVE ALL ⋯paragraph wrapper tags EXACTLY”. If the input doesn’t have any, should I add them? The instructions say “if input has N paragraph tags, output must have exactly N paragraph tags with matching IDs”. Since N=0 here, I should output 0 paragraph tags.

So the correct output should just be: Liu Qihong

But let me, The user has provided a very short input: "刘奇洪". This appears to be a Chinese name. Let me analyze the requirements:

1. The user wants me to translate from Simplified Chinese to English
2. I need to preserve LaTeX commands and MATH placeholders - but there are none here
3. I need to preserve citation commands - but there are none here
4. I need to preserve …tags - but there are none here
5. Maintain academic tone and formal scientific writing style
6. Use precise technical terminology from the glossary - but "刘奇洪" is a name, not a technical term
7. Preserve section structure and paragraph organization - there' s just a name

The glossary provided is: - 机器学习 => machine learning - 深度学习 => deep learning

But these don' t apply to a personal name.

The name "刘奇洪" is a Chinese personal name. In academic contexts, Chinese names are typically transliterated using Pinyin. The standard format for English academic papers is: - Family name (surname) first, followed by given name - Or given name first, followed by family name

The most common and formal approach in English academic writing is to use the format: Given name + Family name, or sometimes Family name, Given name.

For "刘奇洪": - 刘 (Liú) is the family name (surname) - 奇洪 (Qíhóng) is the given name

In English academic contexts, this would typically be written as: - "Qihong Liu" (given name + family name, most common) - Or "Liu, Qihong" (family name, given name)

The most standard and widely accepted format in English academic papers is "Qihong Liu".

Since there' s no tag, no LaTeX, no citations, and no technical terms from the glossary, I should just provide the transliterated name in the appropriate academic format.

The user says "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)." So I should just output "Qihong Liu" without any additional text or formatting.

Wait, let me double-check the requirements. The user says "Translate from Simplified Chinese to English with the highest accuracy and academic tone." A name isn' t really "translated" but "transliterated" or "romanized". The academic standard is to use Pinyin

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Abstract

This study introduces the principle of core power calculation for the KME system in nuclear power units. The core power is calculated and verified using two versions of water and steam property formulas—IFC-67 and IAPWS-IF97. Results indicate that the IAPWS-IF97 formula yields a smaller core power value, primarily because it calculates main steam enthalpy to be 0.8 kJ/kg lower than IFC-67. Adopting the IAPWS-IF97 formula in the KME system can increase unit output by approximately 0.5 MW compared to using IFC-67.

Full Text

Study on the Deviation between IFC-67 and IAPWS-IF97 Formulas in Reactor Core Power Calculation

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Abstract

This paper introduces the principle of calculating reactor core power using the KME system in nuclear power units. The core power of the KME system was calculated and verified using two versions of water and steam property formulas, IFC-67 and IAPWS-IF97. It was found that the core power calculated using the IAPWS-IF97 formula is smaller. The main reason is that the main steam enthalpy calculated by IAPWS-IF97 is 0.8 kJ/kg lower than that of IFC-67. If the KME system adopts the IAPWS-IF97 formula, the unit output can be increased by approximately 0.5 MW compared to using IFC-67.

Keywords: KME system; reactor core power; steam generator; unit output

Introduction

Reactor core power is a crucial monitoring parameter in nuclear power plants. There are several calculation methods, such as rough calculation using sensors outside the reactor pressure vessel to measure neutron flux distribution, calculation based on primary loop medium flow rate and enthalpy rise, and calculation based on secondary loop medium flow rate and enthalpy rise. Since the flow rate, temperature, and pressure measurement instruments in the secondary loop have high precision and are more convenient to maintain, the core power calculated based on secondary loop medium flow rate and enthalpy rise is more accurate and is often used as a benchmark to correct other core power measurements for core monitoring.

The system that calculates core power through secondary loop medium physical parameters is the KME system. Early domestic nuclear power plant KME systems used the IFC-67 formula to calculate core power, and most CPR1000 unit KME systems also use IFC-67, while internationally, the water and steam property formula has been updated to IAPWS-IF97. There are many studies comparing these two formulas for calculating water and steam properties [1]. However, there is little domestic research on the deviation between these two versions in core power calculation. It is necessary to conduct research, which has guiding significance for KME system design.

The following first introduces the principle of core power calculation in the KME system, then manually verifies the core power of a nuclear power plant using both IFC-67 and IAPWS-IF97 versions of water and steam property formulas to identify the deviation between the two formulas in core power calculation.

1. Core Power Calculation Principle

The KME system calculates core power by performing a KME thermal balance test on the KME processing computer. Based on the secondary side feedwater pressure, feedwater temperature, feedwater flow rate, main steam pressure, and blowdown flow rate collected by KME system instruments, the secondary loop thermal power is calculated. According to the principle of energy conservation, the primary loop thermal power equals the secondary loop thermal power. The thermal power input to the secondary loop from sources other than the core can be considered constant (11 MW). Subtracting 11 MW from the secondary loop thermal power yields the core power.

The principle of core power calculation is shown in Figure 1 [Figure 1: see original paper]. According to the energy balance principle, the steam generator thermal power is:

$$W_{SG} = H_v Q_v + H_p Q_p - H_e Q_e$$

Where W_R is core power (MW), W_{SG} is thermal power of a single steam generator (i=1~3) (MW), $W_{\Delta P_r}$ is heat from other sources input to the primary coolant (MW), Q_e is steam generator feedwater flow rate (t/h), Q_p is steam generator blowdown flow rate (t/h), Q_v is steam generator steam flow rate (t/h), H_e is steam generator feedwater enthalpy (kJ/kg), H_p is steam generator blowdown enthalpy (kJ/kg), H_v is steam generator wet steam enthalpy (kJ/kg), and x is steam dryness at steam generator outlet (dimensionless).

For wet saturated steam, the wet steam enthalpy is expressed as:

$$H_v = H_{sat,water} + x \cdot H_{latent}$$

where $H_{sat,water}$ is saturated water enthalpy corresponding to main steam pressure (kJ/kg) and H_{latent} is latent heat of vaporization (kJ/kg).

From formulas (1) to (4), we can derive:

$$W_R = \sum_{i=1}^{3} [H_{vi} - H_{ei}]Q_{ei} - H_{vi} - H_{pi}Q_{pi}] - W_{\Delta P_r}$$

The total blowdown flow rate of three steam generators is measured by flow sensor APG004MD, and each steam generator' s blowdown flow rate is treated as equal, so each is 1/3 of the total flow rate. $W_{\Delta P_r}$ is a constant, which is 11 MW for CPR1000 units and obtained through tests for new models.

2. Verification and Comparison Method

Pressure, temperature, and flow rate data are obtained from the original data collected by the KME system. Enthalpy, specific volume, and dynamic viscosity are calculated using an Excel plugin for water and steam properties. When using the plugin, the IFC-67 and IAPWS-IF97 formulas are selected respectively. Core power is manually calculated through Excel spreadsheets based on the original KME system data. The deviation between IFC-67 and IAPWS-IF97 formulas in core power calculation is compared, and the accuracy of the KME system core power calculation is verified.

3. Example Application

Taking a nuclear power unit as an example, the reactor of this unit has 3 loops, corresponding to 3 steam generators abbreviated as SG1, SG2, and SG3. The KME system is designed based on the product of French EDF company, and the formula for calculating water and steam physical property parameters uses IFC-67. The constants used in core power calculation include gravitational acceleration 9.7882 m/s^2, steam quality 0.999080, and the data in Table 1 . Secondary loop medium parameters use the arithmetic mean of 20 minutes of data collected by the KME system, with the data list shown in Table 2 .

3.1 Main Steam Pressure and Enthalpy Verification

3.1.1 Main Steam Pressure Correction Based on main steam pressure and humidity, the enthalpy value can be automatically calculated by calling the water and steam property plugin in Excel. The calculation of main steam enthalpy requires the absolute total pressure at the steam generator outlet. However, the field measurement is relative static pressure, which requires correction calculation. The correction principle is shown in Figure 2 [Figure 2: see original paper]. The main steam pressure correction formula is:

$$P_v = P_{v,static} + P_{atm} + \Delta P_{dynamic} + \Delta P_{watercolumn}$$

Where P_v is absolute total pressure at steam generator outlet main steam (bar.a), $P_{v,static}$ is relative static pressure measured by pressure transmitter (bar.g), P_{atm} is atmospheric pressure (bar.a), $\Delta P_{dynamic}$ is dynamic pressure (bar), and $\Delta P_{watercolumn}$ is pressure of water column in the pipe (bar). ρ is density of water in the impulse pipe, calculated by the water and steam property Excel plugin based on pressure and temperature in the impulse pipe, and h is water column height difference in the impulse pipe.

ΔP is the pressure loss from the steam generator outlet to the main steam pipe pressure measurement point (bar). ΔP is calculated according to the empirical formula in the French EDF company' s "SG50" test guidelines. The empirical formulas for ΔP are:

$$\Delta P_{SG1} = \left(\frac{Q_e}{3.6 \times 1935.6}\right)^2 \cdot 0.24$$

$$\Delta P_{SG2} = \left(\frac{Q_e}{3.6 \times 1935.6}\right)^2 \cdot 0.44$$

$$\Delta P_{SG3} = \left(\frac{Q_e}{3.6 \times 1935.6}\right)^2 \cdot 0.42$$

where 3.6 is a unit conversion coefficient and 1935.6 is the design feedwater flow rate per steam generator (t/h).

3.1.2 Main Steam Pressure and Enthalpy Verification and Comparison The corrected main steam pressure values are calculated according to formulas (6)-(9). Then, based on pressure and dryness, the enthalpy values are obtained using the water and steam property Excel plugin. The calculation results are detailed in Table 3 .

As can be seen from Table 3, the outlet main steam pressures of SG1, SG2, and SG3 calculated using IFC-67 and IAPWS-IF97 formulas are equal, all slightly lower than KME. However, the deviation of SG1 main steam pressure calculation result from the KME system is larger, the reason for which will be analyzed separately later. The main steam enthalpy calculated using IAPWS-IF97 is lower than KME, while the main steam enthalpy calculated using IFC-67 is higher than KME. The main steam enthalpy calculated by IAPWS-IF97 is 0.8 kJ/kg lower than that of IFC-67.

3.1.3 Reason for Larger Deviation in SG1 Main Steam Pressure As can be seen from Table 3, the deviation between SG1 main steam pressure and KME result is 0.29 bar, while the deviations for SG2 and SG3 are 0.1 bar, indicating that SG1 main steam pressure result has larger deviation. As shown in Table 2, the original measured values of steam generator outlet steam pressure for SG1, SG2, and SG3 are very close, with differences within 0.02~0.04 bar, suggesting that the deviation is caused by calculation of correction terms. According to formula (6), the main steam pressure correction terms include $\Delta P_{dynamic}$, $\Delta P_{watercolumn}$, and ΔP_{loss}. Atmospheric pressure P_{atm} and $\Delta P_{dynamic}$ are calculated values that could be erroneous and cause deviation. Upon recalculation, the deviations of correction terms $\Delta P_{dynamic}$ and $\Delta P_{watercolumn}$ from KME are within 0.01 bar. By elimination, the excessive deviation of SG1 main steam pressure from KME result is caused by the correction term ΔP_{loss}. The "SG50" test guidelines indicate that the design values of main steam pipe pressure loss at the outlet of three steam generators are: SG1: 0.24 bar $\pm$ 20%; SG2: 0.44 bar $\pm$ 20%; SG3: 0.42 bar $\pm$ 20%. The pipe distances from the outlet of three steam generators to the main steam pressure measurement point are different, with SG1 being 26 m, SG2 being 59.8 m, and SG3 being 50 m, corresponding to the "SG50" design values. According to formulas (7), (8), and (9), using KME system Q_e and Q_p to calculate ΔP_{loss}, the results are shown in Table 4 .

As shown in Table 4, the deviation of SG1 main steam pipe pressure loss ΔP_{loss} is very small, about 0.2 bar lower than SG2 and SG3. Since the pipe distance of SG1 is shorter than SG2 and SG3 by about 0.2 bar, ΔP_{loss} for SG1 should be about 0.2 bar lower than SG2 and SG3. However, the ΔP_{loss} values for the three steam generators in the KME system only differ by 0.01 bar, which is definitely problematic. It is speculated that KME system used the wrong coefficient in the empirical formula for calculating SG1' s ΔP_{loss}, possibly using 0.42 or 0.44 incorrectly.

3.2 Feedwater Pressure and Enthalpy Verification and Comparison

The principle of feedwater pressure correction is the same as that of main steam pressure. The calculation of feedwater total pressure is shown in formula (10):

$$P_e = P_{e,static} + P_{atm} + \Delta P_{dynamic} + \Delta P_{loss}$$

The pressure is corrected to the steam generator inlet. The empirical formula provided by the "SG50" test guidelines for feedwater pipe pressure loss of three loops is:

$$\Delta P_{loss} = -0.16 \cdot \left(\frac{Q_e}{1935.6}\right)^2$$

Based on the corrected feedwater pressure and the measured feedwater temperature, the feedwater enthalpy can be obtained using the Excel water and steam property plugin. The calculation results of feedwater total pressure and enthalpy are shown in Table 5 .

As can be seen from Table 5, the feedwater total pressures calculated using IFC-67 and IAPWS-IF97 formulas are very close, all about 0.23 bar higher than KME. The main reason is that KME ignores the dynamic pressure correction (correction amount about 0.16 bar). The feedwater enthalpy calculated by IFC-67 is 0.04 kJ/kg lower than KME, and the feedwater enthalpy calculated by IAPWS-IF97 is 0.09 kJ/kg lower than KME, indicating that the results of feedwater enthalpy calculated by the two formulas are very close.

3.3 Feedwater Flow Calculation

3.3.1 Feedwater Flow Calculation Principle The KME system measures ARE feedwater flow through an orifice plate. According to ISO5167 (2003 version) [4], the orifice flow calculation formula is:

$$Q = C \cdot E \cdot \epsilon \cdot \frac{\pi d^2}{4}\sqrt{2\rho\Delta P}$$

where C is the discharge coefficient (detailed later), E is the approach velocity coefficient, ϵ is the flow expansion factor, ρ is upstream fluid density, and ΔP is differential pressure measured by the differential pressure transmitter. For incompressible fluid (feedwater), $\epsilon = 1$.

ISO5167 (2003 version) [4] specifies the calculation formula for standard orifice discharge coefficient C as:

$$C = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0188 + 0.0063A)\beta^{3.5}\left(\frac{10^6}{Re_D}\right)^{0.3} + (0.043 + 0.080e^{-10L_1} -$$

where β is the diameter ratio ($\beta = d/D$), d and D are the orifice diameter and feedwater pipe circular cross-section diameter under operating conditions. The operating condition diameters can be calculated from reference temperature diameters considering thermal expansion:

$$d = d_{20} \cdot [1 + \lambda(t - 20)]$$
$$D = D_{20} \cdot [1 + \lambda'(t - 20)]$$

where λ is the orifice linear expansion coefficient and λ' is the pipe linear expansion coefficient. The orifice plate uses D, D/2 pressure tapping method, with $L_1 = 1$ and $L_2' = 0.47$, and $M_2' = 2L_2'/(1-\beta)$. Since there are vent holes on the top and drain holes on the bottom of the orifice plate, small hole correction needs to be considered when calculating the orifice diameter.

When calculating the discharge coefficient C, the Reynolds number is involved, which is related to C, thus requiring iterative solution. Taking an initial Reynolds number value $Re_D = 10^6$ to calculate the discharge coefficient C, then calculating the assumed flow rate Q_i, and then calculating $Re_D = \frac{4Q_i}{\pi D\mu}$, where μ is dynamic viscosity under operating conditions and D is pipe inner diameter (mm). After multiple iterations, the final flow rate is obtained. When $|Q_i - Q_{i-1}|/Q_i \leq 0.0001$, i.e., precision of 0.01%, the iteration ends. In actual verification, manual iteration is used, and the iteration precision can be higher.

3.3.2 Feedwater Flow Verification and Comparison Feedwater flow calculation results are shown in Table 6 . Using IFC-67 formula to verify feedwater flow, each loop is 0.13 t/h lower than KME, mainly due to different iteration precision. Using IAPWS-IF97 formula to verify feedwater flow, each loop is 0.37 t/h lower than KME, mainly due to calculation deviation between the two formulas as KME uses the IFC-67 formula.

3.3.3 Notes on Feedwater Flow Calculation In feedwater flow calculation, the following issues should be noted: - According to ISO5167 standard, upstream feedwater density and dynamic viscosity should be used to calculate feedwater flow, and the corresponding feedwater pressure and temperature measurement points should be located upstream of the orifice plate. - Orifice diameter should be corrected for small holes.

3.4 Core Power Verification and Comparison

Based on the previously calculated main steam enthalpy, feedwater enthalpy, and feedwater flow rate, substituting into formula (5) yields the core power, as shown in Table 7 .

The core power calculated using IFC-67 is 2880.52 MW, slightly 0.18 MW higher than KME, with a relative deviation of 0.006% from KME, which is very close. This verifies that the KME system (using IFC-67 formula) of a certain power plant is accurate in calculating core power. The core power calculated using IAPWS-IF97 is 2878.95 MW, 1.4 MW lower than KME. The main reason why IAPWS-IF97 calculates lower core power than KME is the difference in main steam enthalpy. IAPWS-IF97 calculates main steam enthalpy 0.8 kJ/kg lower than IFC-67, while the differences in feedwater flow rate and feedwater enthalpy are small and are secondary effects, as shown in Table 8 .

Since the core power calculated using IAPWS-IF97 is lower than that calculated using IFC-67, if the KME system adopts IAPWS-IF97 to calculate core power, operators can appropriately increase the core power when controlling with the same margin, thus increasing unit output by approximately 0.5 MW, bringing economic benefits.

Conclusion

Through comparison of the deviation between the two formulas in core power calculation and verification of the KME system core power, the following conclusions are drawn: 1. Through verification, it was found that the core power calculated by the KME system using IFC-67 formula differs from manual calculation by only 0.18 MW, about six hundred-thousandths of the KME core power, indicating that the KME system calculation is reliable. 2. The core power calculated using IAPWS-IF97 is 1.4 MW lower than that calculated using IFC-67. 3. If the KME system adopts IAPWS-IF97 to calculate core power, operators can appropriately increase core power when controlling with the same margin, thus increasing unit output by approximately 0.5 MW.

The user wants me to translate a "References" section from Chinese to English. Let me analyze the specific requirements:

1. This is a references section from an academic paper
2. I need to handle Chinese characters in author names and journal titles The user is asking me to translate a section of a Chinese academic paper. The section is titled "3. Specific rules:" and the remaining Chinese text is "三, 张".

Wait, let me re-read the instructions carefully. The user says:

"Section:" 3. Specific rules:" Remaining Chinese: 三, 张

You MUST eliminate ALL Chinese characters. Even a single Chinese character will cause failure."

This seems like the user is giving me instructions about how to handle Chinese characters in the translation, not actual content to translate. The "Remaining Chinese: 三, 张" appears to be an example of what needs to be eliminated.

Let me look at the actual content to translate:

It appears there is no actual content provided. The user has only given me the section heading "3. Specific rules:" and some instructions about handling Chinese characters, but no actual Chinese text to translate.

The user is emphasizing that I must eliminate ALL Chinese characters, even a single one will cause failure. But there' s no content provided between the triple backticks.

This is confusing. Let me re-examine the prompt:

The user says: "Section:" 3. Specific rules:" Remaining Chinese: 三, 张

You MUST eliminate ALL Chinese characters. Even a single Chinese character will cause failure.

If you encounter: - Author names → Use pinyin (王伟 → Wang Wei) - Journal names: Use English title if available, otherwise translate the meaning - Institution names: Use official English names when known - Technical terms: Use standard English equivalents - DO NOT leave any Chinese characters

Let me look at the content:

"'

Return the translated section with ZERO Chinese characters."

The triple backticks are empty. There is no actual Chinese text to translate. The user seems to be testing me or there might be an error in the prompt.

Given the context, I think the user wants me to acknowledge that I' ve understood the rules for handling Chinese characters in academic translation. But the instruction says "Return the translated section with ZERO Chinese characters."

Since there' s no actual content to translate, I should probably return just the section heading, or perhaps state that no content was provided. However, the user seems to be very strict about eliminating Chinese characters.

Wait, I need to reconsider. The user might have intended to provide content but it got lost. Or perhaps "三, 张" IS the content to translate? But that doesn' t make sense in the context of "Specific rules" .

Let me think about this differently. The## References

[1] Oguchi K, Miyagawa K. Comparison between the IAPWS-IF97 and the IFC-67 for the Thermodynamic Properties of Water and Steam[J]. Thermal & Nuclear Power, 1998, 49:870-873.

[2] Song Shijia. Thermal Balance Test for Core Power Calculation in Nuclear Reactors[J]. Nuclear Power Engineering, 2002, 23(2):82-86.

[3] Song Shijia. Analysis of Thermal Balance Test for Core Power Calculation at Lingao Nuclear Power Plant[J]. Nuclear Science and Engineering, 2005, 25(3):271-278.

[4] Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full Part2: Orifice plates 5167-2:2003; Supersedes EN ISO 5167-1:1995: EN ISO

Note: Figure translations are in progress. See original paper for figures.