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CORRELATION FOR HEAT TRANSFER COEFFICIENT FOR RAPID COOLING OF NEUTRON VACUUM FURNACES

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ABSTRACT

Developing rapid cooling technology to reduce the prolonged cooldown times of high-temperature neutron vacuum furnaces is highly desirable. Building on previous research, this study focuses on developing a correlation to describe the average Nusselt number as a function of Reynolds number and Prandtl number. Such a correlation offers a promising tool for designing compact neutron vacuum furnaces that maintain cooling performance by optimizing gas mixtures. Experiments were conducted using three pure gases, helium, nitrogen, and argon, as well as a nitrogen-helium mixture at various flow rates. The resulting correlation predicted the experimental Nusselt numbers with a maximum deviation of 15.7%, with over 66% of the data predicted with high accuracy within ±5%.

Keywords: Neutron vacuum furnace; Rapid cooling; Nusselt number; Radiation.

NOMENCLATURE

A_s	Sample surface area (m^2)
C_s	Sample specific heat (J kg^{-1} K^{-1})
m_s	Sample mass (kg)
$\bar{h}$	Average heat transfer coefficient (W m^{-2} K^{-1})
$\overline{Nu}$	Average Nusselt number
$T_{s,in}$	Initial temperatures of the sample (°C)
$T_{s,f}$	Final temperatures of the sample (°C)
Δt	Time required for the cooling process (s)
$\bar{T}_s$	Average temperatures of the sample (°C)
$\bar{T}_g$	Average temperatures of the gas (°C)
Re	Reynolds number
Pr	Prandtl number
ρ	Gas density (kg m^{-3})
μ	Gas dynamic viscosity (Pa s)
V	Gas velocity (m s^{-1})
L	Characteristic length (m)
c_p	Specific heat of gas (J kg^{-1} K^{-1})
k	Gas thermal conductivity (W m^{-1} K^{-1})

Subscripts

corr	Correlated
exp	Experimental

1. INTRODUCTION

Neutron scattering is a highly versatile and powerful technique for exploring the atomic-scale structure and dynamics of condensed matter, complementing structural probes like those employing photons or electrons and standard laboratory methods [1–3]. Neutron scattering has made significant contributions to the fields of physics, engineering, and medicine [4].

A key challenge in using high-temperature neutron furnaces is the lengthy cooldown process, particularly in the vacuum environments of these furnaces. The standard blue-series neutron vacuum furnace, schematically shown in Figure 1(a), is widely utilized for experiments conducted at temperatures ranging from 1500 to 1800 °C. Its design features a resistive heating element encased by several concentric radiation shields. The cooling process in this system relies solely on radiative heat transfer under vacuum conditions. Due to the strong temperature dependence of radiative heat transfer and the furnace's considerable thermal mass, the cooling process becomes notably prolonged, particularly at temperatures below 500 °C [5] until a safe opening temperature of 100 °C, Figure 1b. The severe impact of slow cooling rate on the overall neutron scattering performance has been addressed in previous research [6,7]. To reduce the cooldown time, some neutron facilities employ a technique involving the repeated intermittent backfilling of the furnace with nitrogen or helium gas, followed by evacuating the chamber. While this approach can reduce the overall cooldown duration by 2-4 hours, it introduces temperature fluctuations due to the repeated fill-and-evacuate cycles. Additionally, this method is typically restricted to temperatures below 300 °C to prevent oxidation or stress-induced deformation of the furnace components [8,9]. As a result, an effective cooling solution for neutron furnaces, particularly in the temperature range of 500 – 100 °C, where radiative cooling becomes insufficient, is highly needed.

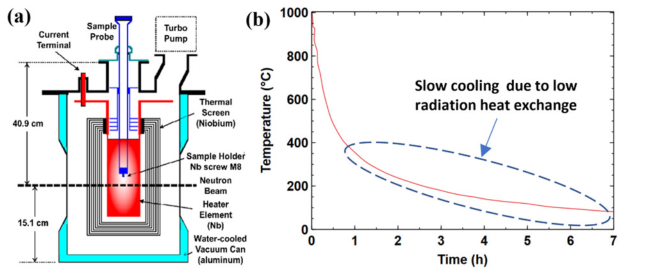

Figure 1: (a) BLUE SERIES NEUTRON FURNACE DESIGN [10] (b) TYPICAL COOLDOWN CURVE FOR VACUUM FURNACE. REPLOTTED FROM [9].

To address the lengthy cooldown period in neutron vacuum furnaces, a new rapid cooling technology was proposed that utilized the closed-loop circulation of low-pressure helium [5]. This new cooling technology demonstrated a significant reduction in the critical 500 °C to 100 °C cooldown phase, cutting the time from multiple hours to less than five minutes in low thermal mass cases without a sample. Additionally, the effects of helium gas mass flow rate and system pressure on cooling time were investigated in [5]. The study revealed that mass flow rate has a dominant influence, whereas system pressure has a negligible impact.

This study continues investigation of proposed rapid cooling system [5]. The present work investigates the effects of different coolants on the cooling rate through experiments with pure helium, pure nitrogen, pure argon, and a nitrogen-helium mixture. A variety of cooling medium options provides operational flexibility and leads to an improved fundamental understanding of the system. An in-house correlation is developed to describe the average heat transfer coefficient as a function of flows' hydrothermal properties in the unique geometric configuration. This is an advancement of our previous work in [5], where the heat transfer coefficients were calculated using an empirical correlation. The present study aims to improve the accuracy of our heat transfer coefficient predictions through in-house correlation development. This correlation will be valuable for optimizing coolant mixtures to achieve higher heat transfer coefficients, thereby enabling faster cooling.

2. EXPERIMENT

The cooling system, illustrated in Figure 2, features key components housed within an external wheeled enclosure, including a low-pressure gas circulation blower, vacuum pump, refrigerant condensing unit with heat exchanger, and PLC control hardware. An ISO 100 tee, capped with a feedthrough endcap, connects the external system to the main furnace volume. Within the furnace, gas is introduced through two inlets connected to proprietary nozzles that penetrate the radiation shields, directing gas between the shields and onto the sample area. A single return hose completes the closed-loop system. Each gas line is equipped with an isolation valve in the intermediate adapter box, enabling vacuum system isolation and independent bypass functionality required for an oxygen purge. The low-pressure system operates between 4 and 14 psi absolute. During cooldown, the pressure in the cooling system and the furnace remains near-equilibrium, as the overall pressure drop for the cooling system is minimal (< 0.1 PSI).

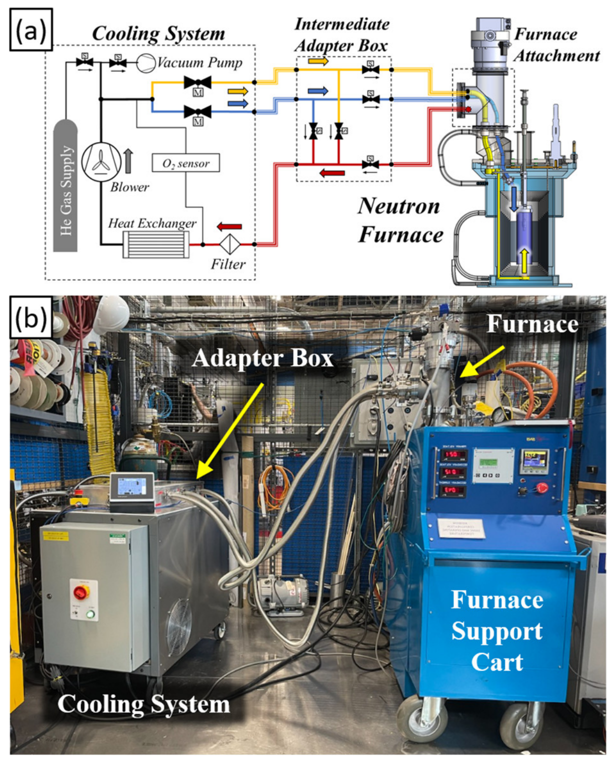

Figure 2: (a) SCHEMATIC OF THE CLOSED-LOOP HELIUM COOLING SYSTEM FOR VACUUM FURNACES; (b) COOLING SYSTEM WITH INLET AND RETURN HOSES CONNECTED TO TEST FURNACE.

Cooldown tests were conducted on the HOT-006 neutron furnace at ORNL and a test furnace at Advanced Cooling Technologies, Inc. (ACT). The ACT test furnace was designed as a thermal analog to HOT-006, with confirmed thermal characteristics comparable to the neutron furnace under both radiation and helium-assisted cooldown scenarios. Mass flow rates were determined using an orifice plate in accordance with the ISO 5167 standard, with a maximum uncertainty of ±10%. Temperature measurements were obtained using a K-type thermocouple positioned at the typical sample location in the furnace's center. No sample was present during these tests, as the focus was on the overall furnace cooldown. Figure 1 provides an overview of the cooling system, and its configuration as tested with the HOT-006 furnace at ORNL.

Each experimental run began with the furnace being evacuated, heated, and maintained at 500 °C for approximately 30 minutes to achieve thermal equilibrium. Oxygen levels were continuously monitored, and purging was performed as needed to keep O_2 levels below 200 ppm. At the start of the cooldown phase, the main solenoid valves were opened to initiate gas flow into the furnace. Gas was maintained at the specified flow rate and pressure throughout the cooling process. Once the furnace core temperature reached 100 °C, the valves were closed to isolate the furnace, marking the end of the cooldown cycle. The entire operation was fully automated using an Allen Bradley PLC, requiring minimal user intervention. Gas flow rate and system pressure were managed automatically through adjustments to pumping speed, gas supply pressure, and vacuum pump activation.

3. RESULTS AND DISCUSSION

The objective of the present study is to develop a correlation that describes the heat transfer coefficient during the cooldown of the sample as a function of the hydrothermal characteristics of the gas. The experiments were conducted using pure helium, pure nitrogen, pure argon, and a nitrogen-helium mixture, at different flow rates.

The energy balance is applied by equating the heat dissipated from the sample to the heat absorbed by the gas flow, as follows:

$$m_s\, C_s \frac{\left(T_{s,f} - T_{s,in}\right)}{\Delta t} = \bar{h}\, A_s\left(\bar{T}_s - \bar{T}_g\right) \tag{1}$$

where $\bar{h}$ is the average heat transfer coefficient; m_s, C_s, A_s represent the sample's mass, specific heat, and surface area, respectively; $T_{s,in}$ and $T_{s,f}$ are the initial and final temperatures of the sample, respectively; Δt is the time required for the cooling process; and $\bar{T}_s$ and $\bar{T}_g$ are the average temperatures of the sample and the gas, respectively. In this study, the average temperatures of the sample and the gas were calculated as the arithmetic means of their initial and final temperatures. With all variables known, the $\bar{h}$ is readily calculated. Then, the average experimental Nusselt number is calculated as follows:

$$\overline{Nu}_{\text{exp}} = \frac{\bar{h}L}{k} \tag{2}$$

where the sample length was used as the characteristic length, i.e., L.

The goal of the present study is to develop a correlation to predict the average Nusselt number as a function of Reynolds number (Re) and Prandtl number (Pr), a widely accepted approach for describing the Nusselt number over a flat plate in forced convection flow [11]. Using the properties of individual gases at the corresponding operating temperatures, Re and Pr are calculated as follows:

$$Re = \frac{\rho V L}{\mu} \tag{3}$$

$$Pr = \frac{\mu c_p}{k} \tag{4}$$

where the velocity used to calculate the Reynolds number is simply obtained by having the mass flow rate, density, and the cross-section area of gas entrance out of a nozzle. The characteristic length in Re is the same as that used for correlating $\overline{Nu}_{exp}$. Also, the properties of the nitrogen-helium mixture are calculated based on the weighted average of the individual gases within the mixture. The desired correlation in this study is the average Nusselt number, as a function of Re and Pr. Based on the data points collected in this study, the final correlation is as follows:

$$\overline{Nu}_{\text{corr}} = 33.22 + 0.028\sqrt{Re} + 188.076 \times Pr^2 \ln Pr \tag{5}$$

Figure 3 compares the experimental and predicted $\overline{Nu}$ obtained by the developed correlation in this study. The difference between the predicted and experimental $\overline{Nu}$ is calculated as $\left(\overline{Nu}_{\text{exp}} - \overline{Nu}_{\text{corr}}\right) \times 100/\overline{Nu}_{\text{exp}}$.

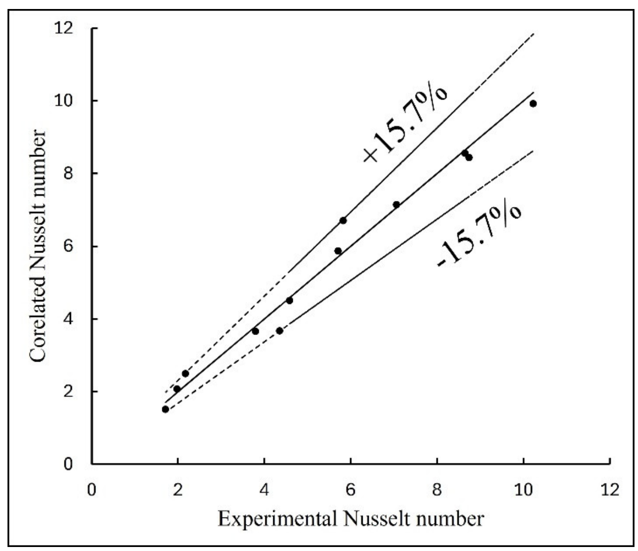

Figure 3: COMPARISON BETWEEN CORELATED AND EXPERIMENTAL NUSSELT NUMBERS.

Overall, the developed correlation in this study predicts the $\overline{Nu}_{\text{exp}}$ with reasonable accuracy. The maximum difference between the predicted and experimental $\overline{Nu}$ is below 15.7%. Importantly, over 66% of the $\overline{Nu}_{\text{exp}}$ are predicted with an accuracy of below 5%, which indicates a good accuracy of the developed correlation to predict $\overline{Nu}$.

The present study serves as an initial effort to develop a correlation to describe $\overline{Nu}$ for the cooling process in neutron vacuum furnaces. Collecting additional data points under a wider range of operating conditions will contribute to the development of a more accurate correlation for $\overline{Nu}$. Such a precise correlation will enable the preparation of gas mixtures as coolants while optimizing overall experimental costs. Furthermore, leveraging this correlation and applying optimization techniques will enable the design of furnaces with reduced sizes without compromising cooling performance.

4. CONCLUSION

The present study investigated the impact of various coolant gases on cooling performance in a novel rapid cooling technology for neutron vacuum furnaces. Cooling rates were examined using pure helium, pure nitrogen, pure argon, and a nitrogen-helium mixture at different flow rates. Based on the collected data, an in-house correlation was developed to describe the $\overline{Nu}$ as a function of Re and Pr. The correlation predicted the experimental $\overline{Nu}$ within ±15.7%, with over 66% of the experimental data showing excellent accuracy, within ±5%. This precise correlation provides valuable insight for designing smaller furnaces without compromising cooling performance by selecting optimal gas mixtures.

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REFERENCES

[1] Cristiglio, V., Cuello, G. J., and Jiménez-Ruiz, M., "Neutron Scattering," *Comprehensive Supramolecular Chemistry II*, Elsevier, 2017, pp. 263–288. https://doi.org/10.1016/B978-0-12-409547-2.12490-4

[2] Haravifard, S., Yamani, Z., and Gaulin, B. D., "Quantum Phase Transitions," *Experimental Methods in the Physical Sciences*, Vol. 48, Elsevier, 2015, pp. 43–144. https://doi.org/10.1016/B978-0-12-802049-4.00002-6

[3] Chen, Y., and An, K., "Unraveling Transition-Metal-Mediated Stability of Spinel Oxide via in Situ Neutron Scattering," *Journal of Energy Chemistry*, Vol. 68, 2022, pp. 60–70. https://doi.org/10.1016/j.jechem.2021.10.024

[4] Hu, H., Zhang, C., Dou, M., Huang, Z., Sun, Y., Ye, F., Yuan, B., Bai, B., Cheng, H., Yang, S., Duan, Y., and Tong, X., "Experimental and Numerical Investigation the Radiant Heating Element in Neutron Scattering Furnace," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 1053, 2023, p. 168317. https://doi.org/10.1016/j.nima.2023.168317

[5] Adhikari, D., Radyjowski, P., Carlson, D., Davis, R., Zou, A., Rao, P., and Chen, C.-H., "Rapid Cooling Technology for Extreme Sample Environment Neutron Vacuum Furnaces," presented at the ASME 2024 Heat Transfer Summer Conference collocated with the ASME 2024 Fluids Engineering Division Summer Meeting and the ASME 2024 18th International Conference on Energy Sustainability, Anaheim, California, USA, 2024. https://doi.org/10.1115/HT2024-130519

[6] Xu, X., Odqvist, J., Colliander, M. H., King, S., Thuvander, M., Steuwer, A., and Hedström, P., "Effect of Cooling Rate after Solution Treatment on Subsequent Phase Separation during Aging of Fe-Cr Alloys: A Small-Angle Neutron Scattering Study," *Acta Materialia*, Vol. 134, 2017, pp. 221–229. https://doi.org/10.1016/j.actamat.2017.06.001

[7] Huston, E. L., Cahn, J. W., and Hilliard, J. E., "Spinodal Decomposition during Continuous Cooling," *Acta Metallurgica*, Vol. 14, No. 9, 1966, pp. 1053–1062. https://doi.org/10.1016/0001-6160(66)90193-3

[8] Niedziela, J. L., Mills, R., Loguillo, M. J., Skorpenske, H. D., Armitage, D., Smith, H. L., Lin, J. Y. Y., Lucas, M. S., Stone, M. B., and Abernathy, D. L., "Design and Operating Characteristic of a Vacuum Furnace for Time-of-Flight Inelastic Neutron Scattering Measurements," *Review of Scientific Instruments*, Vol. 88, No. 10, 2017, p. 105116. https://doi.org/10.1063/1.5007089

[9] Goodway, C., McIntyre, P., Sears, A., Belkhier, N., Burgess, G., Kirichek, O., Lelièvre-Berna, E., Marchal, F., Turc, S., and Wakefield, S., "A Fast-Cooling Mode for Blue Series Furnaces," *Journal of Neutron Research*, Vol. 21, Nos. 3–4, 2020, pp. 137–142. https://doi.org/10.3233/JNR-190128

[10] "1600C Furnace (Https://Www.Nist.Gov/Ncnr/Sample-Environment/Equipment/Furnaces/1600c-Furnace)."

[11] Bergman, T. L., Lavine, A., and Incropera, F. P., "Fundamentals of Heat and Mass Transfer," John Wiley & Sons, Inc., Hoboken, NJ, 2019.

