Natural Convection Heat Transfer with Molten Salt in a Differentially-Heated Cavity

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ABSTRACT

Natural convection is an important mode of heat transfer in the design of passive safety systems for molten salt reactors. While heat transfer correlations for natural convection in water have been widely studied, there is a lack of equivalent experimental data for molten salts. An experimental investigation of convective heat transfer in a differentially-heated cavity using nitrate salts is presented in this paper with the goal of obtaining empirical heat transfer correlations which can be compared to existing correlations. Temperature distributions in the salt and on the cavity boundaries are measured using a combination of infrared thermometry and thermocouple probes, then one-dimensional heat transfer models are used to calculate the total heat flux and heat transfer coefficient. The observed heat transfer rates are found to be overestimated by as much as 120% by existing correlations, and an empirical correlation is proposed to model this data. These findings can provide a basis for the modeling and design of passive safety systems as well as validation data for numerical simulations of natural convection in molten salt.

KEYWORDS
Molten Salts, Natural Convection, Differentially-Heated Cavity, Infrared Thermometry

1. INTRODUCTION

A major feature of Gen IV reactor design is the shift from active to passive cooling. Passive safety systems provide major advantages compared to active systems due to their reduced mechanical complexity and failure modes [1]. While active cooling designs rely on the pumping of coolant to remove heat from the reactor and maintain safe operating temperatures via forced convection, passive cooling relies on natural convection induced by temperature gradients in the coolant. Accordingly, the effective modeling and design of passively cooled reactor systems is dependent on accurate physical modeling of natural convection [2].

Current Gen IV reactor concepts include gas-cooled, water-cooled, and salt-cooled designs. Molten salt reactors (MSRs) are a promising concept due to their ambient operating pressures, eliminating the need for expensive pressure vessels, and ability to burn a broad range of fuels including existing nuclear waste [1]. However, the physics of natural convection at high temperature in molten salts remains an area of active research and further work is required to ensure accurate heat transfer modeling for reactor design.

Empirical correlations are a powerful tool for predicting convective heat transfer rates in a wide range of liquids, and are widely used in the design of heat transfer systems. While much of the early work on

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empirical correlation measurement was conducted on water and air [3] [4], this data has been found to be applicable to a wide range of heat transfer fluids [5] [6]. Such methods have even been found to be applicable to forced and mixed convection problems in molten nitrate salts [7]. However, a recent study by Yu et al. [8] suggested that existing correlations may overestimate heat transfer rates for turbulent natural convection in a low-temperature eutectic mixture of LiNO3-CaNO3-NaNO3-KNO3. This result suggests that further work is required to provide reliable data for heat transfer rates in various molten salt mixtures of interest across a range of Rayleigh numbers.

In this work, we present measurements of the Nusselt number for a eutectic mixture of NaNO3-KNO3 (commonly known as Solar Salt) in a differentially-heated rectangular cavity for Rayleigh numbers ranging from 10^8 - 10^9.

2. NATURAL CONVECTION IN ENCLOSURES

Turbulent natural convection in enclosures is a well-studied phenomenon, with important applications to passive cooling systems and thermal energy storage. Early work in this area includes studies of heat transfer rates in a horizontal layer of water by Chu & Goldstein and Garon & Goldstein, finding that the Nusselt number could be modeled by a power law function of the Rayleigh number for Ra between 10^5 and 10^9 [3] [4]. Globe & Dropkin studied heat transfer rates in silicone oil and mercury in addition to water, and examined the dependence of the Nusselt number on both the Rayleigh and Prandtl numbers [5]. This study found a similar Ra dependence to the aforementioned studies of water and also found that the Nusselt number was proportional to $\mathrm{Pr}^{0.074}$. In general, heat transfer correlations for natural convection in horizontal enclosures can be expressed in the form of Eq. 1 [6] [9]:

$$\mathrm{Nu}(\mathrm{Ra},\mathrm{Pr}) = C\mathrm{Ra}^n\mathrm{Pr}^m \tag{1}$$

A summary of the correlations proposed by the above studies, along with the parameter ranges examined in each study, is given in Table 1. The fit coefficients from this paper, discussed in Sec. 4, are also listed for comparison.

While there is generally good agreement between the above studies using water, air, and other common engineering fluids such as thermal oils, few studies have been performed to demonstrate their applicability to

Table I. Nusselt correlations

Reference	Fluid	Ra	C	n	m
Garon & Goldstein	water	$1.3\times10^7 < \mathrm{Ra} < 3.3\times10^9$	0.130	0.293	0
Chu & Goldstein	water	$2.8\times10^5 < \mathrm{Ra} < 1.1\times10^8$	0.183	0.278	0
Globe & Dropkin	water, silicone oil, mercury	$3\times10^5 < \mathrm{Ra} < 7\times10^9$	0.069	0.333	0.074
Yu et. al	$LiNO_3$-$CaNO_3$-$NaNO_3$-KNO_3	$7\times10^7 < \mathrm{Ra} < 1.2\times10^9$	0.0445	0.308	0
Current Work	$NaNO_3$-KNO_3	$2\times10^8 < \mathrm{Ra} < 2\times10^9$	0.037	0.291	0

molten salts, which have significantly higher operating temperatures and Pr than these other fluids. Bin et al. studied the applicability of existing correlations to turbulent forced convection of molten lithium nitrate for $2{\times}10^4$ < Re < $5{\times}10^4$ and 12.7 < Pr < 14.7 [7]. This data showed good agreement with various correlations including those of Sieder-Tate, Petukhov, and Hausen, suggesting that existing correlations can be used for modelling forced convection of molten nitrates. However, Yu et al. found that existing correlations including those of Chu $\&$ Goldstein, Garon $\&$ Goldstein, and Globe $\&$ Dropkin significantly over-predict the Nusselt numbers observed for natural convection of a low-temperature nitrate eutectic mixture [8]. The authors proposed a new correlation based on this data, shown in Table I, which is dependent only upon Ra.

3. EXPERIMENTAL PROCEDURE

3.1. Experimental Setup

Fig. 1 shows the schematic diagram of the experimental setup. An alumina crucible is filled with salt and heated from below, with the top of the crucible open so that the top surface of the salt will be cooled by the surrounding air. A custom heater was designed to provide a maximum power of 1500 W at temperatures up to 800 °C; this heater consists of a steel plate which encloses a radiative heating panel in order to provide a uniformly heated surface on which to place the crucible. The crucible and heater are insulated with 10 cm of high-temperature ceramic fiber insulation in order to reduce heat losses to the surroundings and create approximately adiabatic side wall boundary conditions for the cavity.

The temperature at the heated bottom surface of the salt, T_h, was measured directly using a thermocouple inserted from the open crucible top and placed in contact with the bottom crucible surface. Type K thermocouples were used, with an accuracy of max(2.2 °C, 0.75$\%$).

Reliable and precisely repeatable measurement of the temperature, T_c, of the exposed top surface of the salt using a thermocouple positioned at the salt surface was challenging since the salt height changed significantly between measurements. Instead, T_c was measured using a FLIR A700 IR camera. An example of

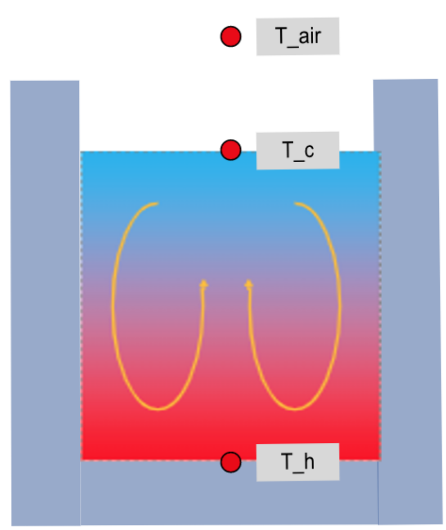

Figure 1. Schematic diagram of experimental setup for natural convection of molten salt.

this data is shown in Fig. 2. Note that the thick line of low temperatures is due to the thermocouple used to measure T_h, as labelled in the figure. The measured value of T_c was taken as the average temperature of the salt surface. The uncertainty on this measurement was calculated as max(2 °C, 0.75%).

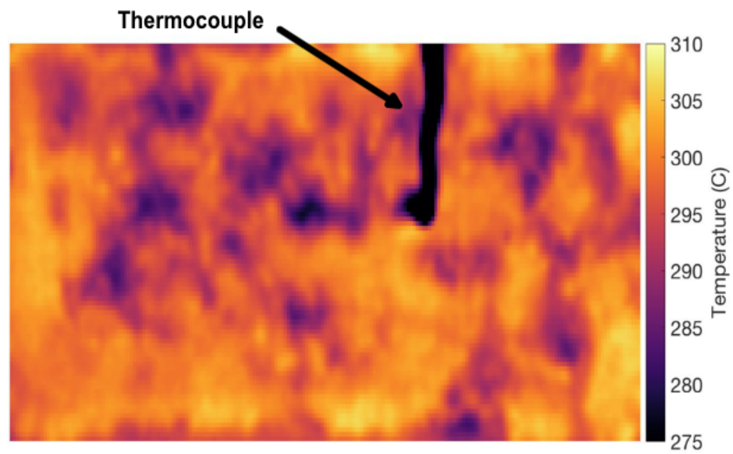

Figure 2. IR camera measurement of salt top surface temperature.

3.2. Experimental Data Analysis

The flux passing through the salt from the heated bottom wall, Q_s, is difficult to obtain via measurements of the heater power or hot plate temperature distribution due to imperfect insulation of the heater and unknown contact resistances between the heater and crucible. Instead, the value is calculated by assuming that heat losses through the crucible side walls can be neglected and that 100% of the flux through the salt leaves through the exposed top surface. Given this assumption, we can evaluate Q_s by calculating the heat lost to the surroundings through the top surface.

Q_s is assumed to consist of two components: the convective losses from the top surface, Q_{conv}, and the radiative losses from the top surface, Q_{rad}. Q_{conv} is calculated according to Eq. 2, which uses the correlation for a horizontal plate cooled from above given by Cengel & Ghajar, $\mathrm{Nu} = 0.59\mathrm{Ra}^{1/4}$ [9].

$$Q_{conv} = hA\Delta T \tag{2}$$

Q_{rad} is evaluated using a gray surface-to-surface radiation model. The problem geometry is shown in Fig. 3, and the resistance network model used to solve for Q_{rad} is shown in Fig. 4. The temperature of the wall used for surface 2 is assumed to be equal to the average salt surface temperature used for surface 1, while the temperature of the surroundings used for surface 3 is measured using a thermocouple suspended 30 cm above the crucible. The surface emissivities of solar salt was taken as $\epsilon_1 = 0.9$ [10], while the wall emissivity was taken as $\epsilon_2 = 0.25$ [11]. Surface 3 was assumed to be a blackbody with $\epsilon_3 = 1.0$.

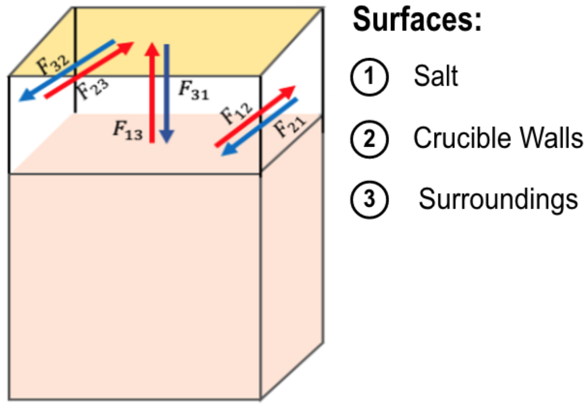

Figure 3. Geometry of surface-to-surface radiation problem for losses from salt surface. Salt (surface 1) shown in pink, exposed crucible walls (surface 2) shown in white, and crucible opening to surroundings (surface 3) shown in yellow.

The problem of calculating the flux Q_{rad} leaving the salt surface can be modeled as gray surface-to-surface radiation in a three-surface enclosure and solved by constructing the equivalent thermal resistance network according to Eq. 13-41 of Cengel & Ghajar [9]. The equivalent thermal resistance network is shown in Fig. 4; $Q_{rad} = Q_1$ is obtained by solving for the fluxes Q_1,Q_2,Q_3 which satisfy the condition that the algebraic sum of the currents at each node (highlighted in red) must equal zero.

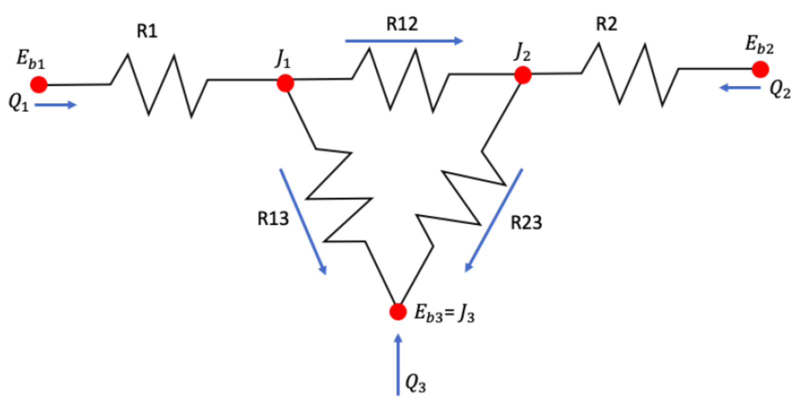

Figure 4. Equivalent resistance network for radiative exchange between salt surface, crucible walls, and surroundings.

Once Q_s has been obtained by summing the contribution of the convective and radiative losses calculated above, the Nusselt number is calculated according to Eq. 3:

$$\mathrm{Nu} = \frac{Q_s L_c}{k A \Delta T} \tag{3}$$

where L_c is the characteristic length scale of the flow. For the rectangular cavity under consideration, L_c is equal to the height of the salt layer. ΔT is equal to the difference between T_h and T_c, while A is the cross-sectional area of the salt layer and k is the thermal conductivity of the salt.

With these measurements of T_h, T_c, and Q_s, we can calculate the Ra, Pr, and Nu values for each data point and perform a non-linear least squares fit to find a correlation of the form given in Eq. 1.

4. RESULTS & DISCUSSION

Preliminary data displaying the relationship between Nu and Ra is shown in Fig. 5. The correlations of Globe & Raithby, Garon & Chu, and Yu et al. are displayed alongside the data for comparison. This data supports the suggestion of Yu et al. that the Nusselt number of nitrate salts is greatly overestimated by correlations obtained via experiments with water and oils. While the present data displays slightly higher Nu values than their correlation predicts, an agreement within 2 standard deviations is observed for all measurements compared to the wide discrepancy observed between our data and the correlations of Garon & Chu or Globe & Raithby. The correlation of Garon & Chu overpredicts these data points by 120%. The differences between these two data sets for nitrate salts may be explained by the use of different salt mixtures as well as the different geometries studied.

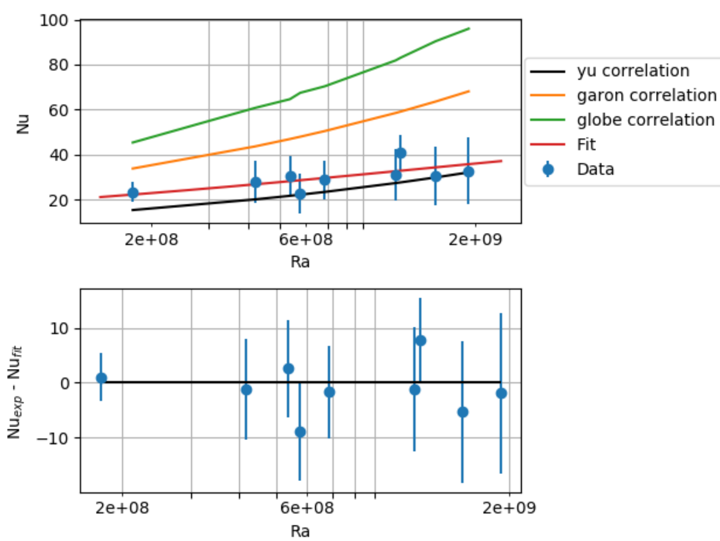

Figure 5. Dependence of heat transfer rates on Rayleigh number for experimental data and empirical correlations. Yu et al. correlation and Garon & Goldstein correlation are shown alongside a least-squares fit of the data. Non-linear least-squares fit is also shown. Residuals for the least-squares fit are plotted below.

Fig. 6 shows the relationship between Nu and Pr. The inclusion of Pr in correlations of the form of Eq. 1 differs between studies. While Bin et al. found that Pr was a relevant variable for predicting Nu in forced convection of molten nitrate salt [7] and it has been included in a number of correlations for natural convection [6] [9], the correlation proposed by Yu et al. did not contain a Pr-dependence [8]. In order to assess the influence of Pr on the measured Nu values, this relationship was plotted in Fig. 6.

Since it is difficult to evaluate whether the values of Nu and Pr are correlated by inspection alone, linear regression is used to test for statistically significant correlation. The data is linearized so that a linear regression can be performed of the form shown in Eq. 4.

$$\log(\frac{\mathrm{Nu}}{\mathrm{Ra}^{1/3}}) = m\log(\mathrm{Pr}) + \log(C) \tag{4}$$

The correlation coefficient, r, found by a linear regression of the data in this form can be used to determine whether there is in fact a functional relationship between these two linearized variables. For a dataset with $N = 9$ samples, a value of $r > 0.666$ is required to confirm a functional relationship with a 95% confidence level. As our data has a value of $r = 0.359$, we cannot be confident that a relationship exists. This result suggests that the omission of Pr from our correlation, equivalent to setting $m = 0$ in Eq. 1, is justified by this preliminary data.

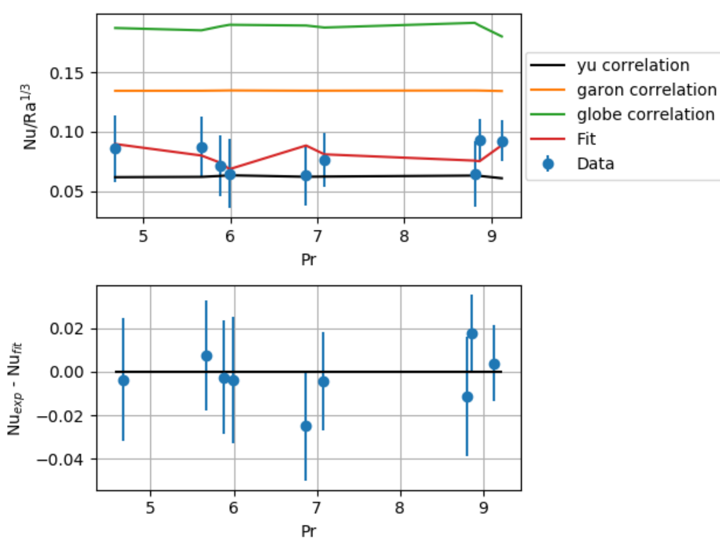

Figure 6. Dependence of heat transfer rates on Prandtl number for experimental data and empirical correlations. Yu et al. correlation, Garon & Goldstein correlation, and Globe & Raithby correlation are evaluated at each data point and shown alongside a least-squares fit of the data. Residuals for the least-squares fit are shown below.

Setting $m = 0$, a nonlinear least-squares fit of the data to Eq. 1 is performed. The obtained fit values of $C = 0.037$ and $n = 0.291$, listed in Table I, are comparable to the parameters of Yu et al. as expected due to the similar working fluid and range of Rayleigh number.

4.1. Uncertainty Analysis

Error bars for the data points displayed in Fig. 5 and Fig. 6 are estimated based on the propagation of uncertainties on the measured quantities used to calculate Nu. These quantities include the salt temperatures T_h

and T_c, the air temperature T_a, and the material properties obtained from literature values. The thermophysical properties for solar salt reported by the salt supplier were assumed to have an uncertainty of 10% [12]. The salt surface emissivity reported by [10] was also assumed to have an uncertainty of 10%.

In order to identify major sources of uncertainty in our results, the contributions of each measured or referenced quantity to the overall uncertainty on derived values including Ra, Pr, Q_s, and Nu was evaluated and displayed in Fig. 7. The contribution of each source to the total uncertainty on the derived value was calculated by setting the uncertainty of all other sources to zero and evaluating the model for the derived quantity and its uncertainty. This uncertainty was then normalized by the value of the derived quantity.

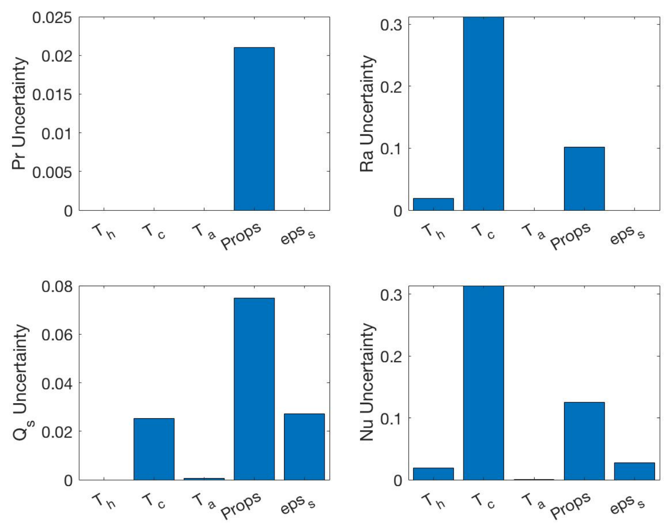

Figure 7. Contributions of measurement uncertainties and material property uncertainties to the propagated uncertainties on derived quantities. Uncertainties for each derived quantity have been normalized by the value of the derived quantity.

5. CONCLUSIONS

By investigating the relationship between Nu and Ra in a differentially-heated cavity, the overestimate of heat transfer rates by widely-used empirical correlations for natural convection when applied to molten nitrate salt has been demonstrated. A comparison between data obtained with solar salt for $2\text{x}10^8 < \text{Ra} < 2\text{x}10^9$ and various correlations obtained via measurements of water and other low-temperature fluids shows that further work is required to obtain accurate correlations for applications in the design of molten salt reactors. The relationship between Nu and Pr was also investigated, finding no statistically significant correlation between the two variables and suggesting that a correlation of the form Nu = Nu(Ra) may be sufficient for accurate predictions of heat transfer rates in this experiment. This improved understanding of the variables affecting heat transfer rates in molten nitrate salts will contribute to the accurate modeling of molten salt thermal hydraulics, with important applications to the design of passive cooling systems in molten salt reactors.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), funding reference number RGPIN-2019-05845, and the Fonds de recherche du Québec – Nature et technologies (FRQNT), funding reference 2022-NC-298727. The authors would also like to thank Sociedad Química y Minera (SQM) for donating the nitrate salts.

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