DIRECT STEAM INJECTION HEATING OF LIQUID FOOD PRODUCTS

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DIRECT STEAM INJECTION HEATING OF LIQUID FOOD PRODUCTS

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LIST OF NOMENCLATURE

A_0-A_8	Psychometric Constants
A	Cross Sectional Flow Area, m^2
c_P	Specific Heat, $kJkg^{-1}C^{-1}$
CWH	Condensation Induced Water Hammer
d	Diameter of Interior Concentric Pipe, m
D	Diameter of Exterior Concentric Pipe, m
d_c	Characteristic Dimension, m
d_h	Hydraulic Diameter, m
DSI	Direct Steam Injection
E	Error
FAPC	Food and Agricultural Products Center
h	Convective Heat Transfer Coefficient, $Wm^{-2}C^{-1}$
h_{LG}	Enthalpy of Evaporation,
Ja	Jacob Number
k	Thermal Conductivity, $Wm^{-1}C^{-1}$
L	Characteristic Length of Flow Geometry, m
N	Model Output
n	Number of Components to be Summed
Nu	Nusselt Number
P	Wetted Perimeter, m
Pe	Peclet Number
Pr	Prandtl Number
P_s	System Operating Pressure, psi
q	Heat Flux, $Btuhr^{-1}ft^{-2}$
R^2	Coefficient of Determination
Re	Reynolds Number
r_h	Hydraulic Radius, m
R_T	Thermodynamic Ratio
RTD	Resistive Thermal Device
St	Stanton Number
T_∞	Liquid Temperature, °C

t_{iw}	Initial Temperature of the Wall, F
T_f	Final Temperature of the Product at onset of CWH, K
T_i	Initial Temperature of the Product, K
T_{sat}	Saturation Temperature of the Product, K
t_{vs}	Saturation Temperature of the Steam, F
u	Product Velocity, ms^{-1}
u_i	Model Input Variables
V	Product Velocity, ms^{-1}
X_i	Mass Fraction of the i^{th} Component
α	Thermal Diffusivity, m^2s^{-1}
μ	Product Viscosity, cP
ρ	Product Density, kgm^{-3}
ρ_G	Density of Gas, kgm^{-3}
ρ_L	Density of Liquid, kgm^{-3}

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CHAPTER I

INTRODUCTION

Heating of food products can cause many useful changes to a product's taste, texture, and appearance. In addition to these changes, many of the most useful impacts of thermal processing on the food product occur on a cellular level, including the inactivation of enzymes and the destruction of pathogens that can cause spoilage. Pasteur's discovery that microbial metabolism is the driving force behind the fermentations that spoil food products (Lewis and Heppell, 2000) brought to light the importance of the commercial sterilization of food products.

There are many methods of thermal processing used in the food industry. Techniques range from batch processing to continuous processing and from indirect heat exchange to direct heat transfer. Direct Steam Injection (DSI) heating, the thermal processing method that is the focus of this research, has not found widespread acceptance in the industry. Despite the benefits of highly efficient heat transfer in a continuous flow system, the occurrence of Condensation-induced Water Hammer (CWH) and the associated noise, system damage, and operator hazards have deterred processors from using DSI systems (Lewis and Heppell, 2000; Schroyer, 1997).

The purpose of the research described herein, was to examine relationships between the operating conditions of a DSI system, the physical properties of liquid food products, and the occurrence of CWH. The goal was to investigate a mathematical relationship that processing plant managers and DSI system operators could use to predict safe operating conditions. Such an equation was developed by Bowser et al. (2003) based on the thermodynamic ratio (R_T) and the Peclet Number (Pe) using data collected in tests of water and sugar water. The following research first repeated the experiments reported by Bowser et al. (2003) testing water and sugar solution, then examined the applicability of the relationship determined by Bowser et al. to beef stock and corn starch, and finally looked at the use of other dimensionless parameters that are commonly used to describe heat transfer and fluid flow to see if another relationship could be defined.

CHAPTER II

LITERATURE REVIEW

Thermal Processing of Liquid Food Products

Batch processing is an inexpensive and flexible method for heating foods. In batch processing, a unit of product is introduced into the heating apparatus, brought up to temperature, held for sterilization time if required, and removed from the heater. This method, used in steam-jacketed kettles and retorts, can be applied to virtually any food product (Lewis and Heppell, 2000).

In heat transfer, temperature is a function of location and time (Singh and Heldman, 2001). Therefore, the distance from the heating source to the center of the product determines the time that a product must be exposed to high temperatures. While heating can have beneficial effects on the food product, prolonged exposure to heat or heating at high temperatures can have adverse effects on the taste, texture, appearance, and nutritional characteristics of a product (Lewis and Heppell, 2000). Therefore, processors have turned to continuous heating techniques over batch processing for pumpable products in order to reduce the distance from the heat source to the center of the product and therefore the reduce time required for heating.

In continuous processing, heat is transferred to a product as it flows through a heat exchanger, with the hold time required for reducing microbial activity determined by the product flow rate and the equipment properties including tube diameter and length. The thermal death time of microbes decreases as temperature increases, and because the desired temperature can be reached faster in continuous processing than in batch processing, the product is not required to be at a high temperature for a prolonged period. In addition to the increased product quality that results from a shorter exposure to high temperatures, continuous processing may have economic benefits from a higher production rate and less materials handling (Kundra and Strumillo, 1998). Continuous thermal processing techniques include methods that employ electrical energy for heating and methods that utilize heat from hot water or steam, with the later method being of interest for this research.

Processes that use hot water or steam for heat transfer can be further divided into indirect methods and direct heating methods. Indirect methods are those in which there is a heat exchange surface separating the heating medium from the product to be heated, for example plate, tubular, and scraped surface heat exchangers. Direct methods such as steam infusion or steam injection have direct mixing of the heating medium and the product (Kudra and Strumillo, 1998).

Direct Steam Injection Heating

In a direct steam injection system, food grade steam is injected directly into the food product. This can be done simply through a single-orifice venturi as shown in Figure 1. However, this method must have high velocity steam and a long stretch of straight pipe downstream in order to ensure proper mixing and there is a large pressure drop across the device (Lewis and Heppell, 2000).

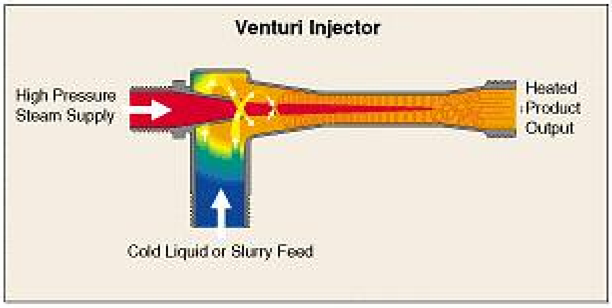

Figure 1: Single orifice venturi direct steam injector (Perry, 1998).

A multiple-orifice DSI heater is an improvement over the single-orifice models for food processing applications. In this design, steam is injected into the product through many small holes in a central tube. The central tube contains a spring loaded piston that regulates the steam pressure in relation to the product pressure. Helical flights aid in mixing the steam with the product within the mixing chamber. The DSI heater used in this research is shown in Figure 2 (Pick Heaters, West Bend, WI Model SC2-3). A disassembled view of the heater body is shown in Figure 3. The small holes in the injector tube ensure that the steam is introduced into the product in the form of small bubbles, which produces a more rapid condensation and thus virtually instantaneous heating. In fact, Burton et al. (1977) found that full temperature could be reached just 0.9 seconds after steam injection. Rapid condensation is also important to minimize uncondensed steam bubbles in downstream piping, and maximize product throughput. Rapid condensation can also be encouraged by providing product backpressure on the injector greater than the pressure required to prevent boiling (Lewis and Heppell, 2000).

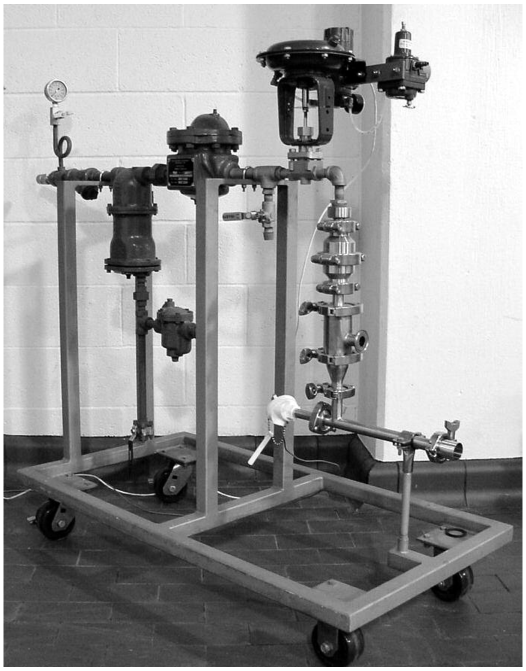

Figure 2: Pilot scale steam injection heater (Pick Heaters, West Bend, WI Model SC2-3) (photo courtesy of the Food and Agricultural Products Center, Oklahoma State University, Stillwater, OK).

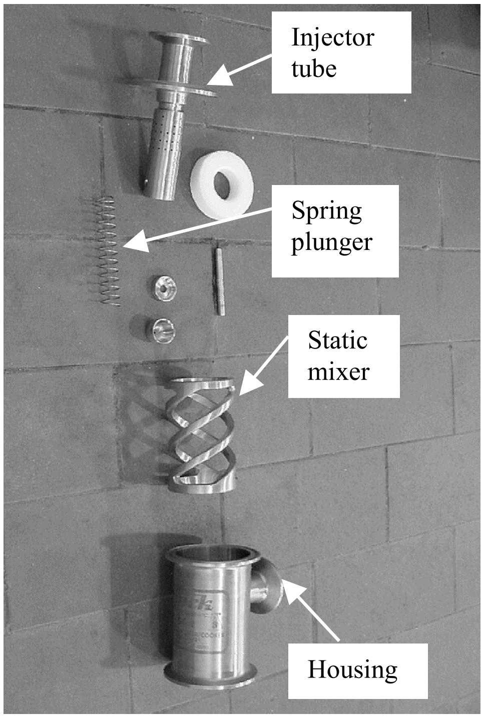

Figure 3: Disassembled view of the multi-orifice steam injection heater body used in this study (photo courtesy of the Food and Agricultural Products Center, Oklahoma State University, Stillwater, OK).

When the steam is injected into the product, it condenses, giving up some of its sensible heat and its latent heat of vaporization. This condensate can cause considerable dilution, with a 60°C increase in product temperature adding about 11% of water to the product (Lewis and Heppell, 2000). In many food processing applications, dilution is acceptable; but for applications where additional water is not desirable, the condensate can be removed from the product after heating using a vacuum chamber.

Direct heating is a much more efficient heating method than indirect heating. Indirect heating only utilizes sensible heat, meaning that, when using hot water as the heating medium, only 4.2kJ of heat is available per kilogram of water for every degree difference between the temperature of the product and the temperature of the heating water. However, DSI heating employs the latent heat of vaporization of steam (2260 kJ kg^{-1}), in addition to the sensible heat. On a per-degree-basis, the heat content of steam is 540 times that of water (Alverez et al., 2000). In fact, Jones and Larner (1968) found that the heat transfer coefficient of a DSI system was 60 times greater than of indirect steam heating systems. This high efficiency leads to energy savings for producers; Sutter (1997) found that a DSI systems used 7.9% less energy than a shell and tube heat exchanger when heating water and Schroyer (1997) stated that reductions in energy demands of 20-25% were common.

Precise and flexible temperature control is another major benefit to steam injection heating. DSI units can be used for raising product temperature by as little as 5.5°C to much larger increases of 96.7°C just by varying the amount of steam added to the product (Singh and Heldman, 2001). In addition, product heating begins as soon as the steam valve is opened and ends as soon as it is closed, so DSI systems do not require a long warm-up period and have fewer problems with overshooting the set point temperature due to residual heat in the system (Schroyer, 1997). Finally, Alverez et al. (2000) found that when heating beer mash, DSI was preferred over batch processing. He found there was a reduced risk of scorching the mash, because the steam remained at a constant temperature, limiting the temperature of the final product.

In addition to the high efficiency, instantaneous heating, and precise temperature control of DSI, benefits over indirect heat exchangers include less space requirements, no need for condensate return systems (Schroyer, 1997), increased temperature control (Sutter, 1997), the ability to process more-viscous products, and less fouling (Lewis and Heppell, 2000).

Steam injection heating has found utility in a wide variety of applications. In the field of biotechnology, it has been found that steam injection heating does not require a product to be held at high temperatures for as long as batch processing does to achieve the same result. Biotechnology products that benefit from a shorter exposure to high heat include thermolabile bio-materials, applications that require constant dry matter content after heating, and bio-material broths that contain starch that otherwise could be gelatinized. (Kudra and Strumillo, 1998). Industrial facilities that already posses a steam supply have found that steam injection heating is an efficient means of producing hot water for use throughout the facility. For example, steam heated hot water can be used instead of steam in a jacketed kettle to produce more even heating and better temperature control of the product (Sutter, 1997). In the food processing arena, steam injection can be used to heat almost any pumpable product. Some designers advocate that it is most applicable to low viscosity and homogenous products such as milk and juices (Richardson, 2001). However, it has also been employed to heat soups, chocolate, processed cheeses, ice cream mixes, puddings, fruit pie fillings (Singh and Heldman, 2001), jams, cheeses, salsa, pet foods, sugar and starch candy mixtures (Pick Heaters, 2004), beer mash (Alverez et al, 2000), baby food, and texturized proteins (Bowser et al, 2003).

Condensation-Induced Water Hammer

Condensation-induced water hammer is a major drawback of DSI heating systems. This phenomenon can occur when a high pressure steam bubble is surrounded by product. As the steam condenses due to heat loss to the product, the volume of the condensate is much less than the volume of the steam. The pressure within the bubble drops drastically causing the bubble to collapse. Bubble collapse can cause large pressure surges that propagate within the system and cause loud noise (Van Duyne et al., 1989). Lewis and Heppell (2000) suggested that “some form of sound absorption may be necessary” to cover up this problem. However, the issue goes beyond simple noise. The forces on the system piping and valves can be large enough to cause costly damage and may be hazardous to operators. Therefore, it is important to define the operating conditions under which CWH will occur so as to allow processors to implement DSI systems and avoid the undesirable effects of CWH.

Bowser, et al. (2003) addressed the concern of designing DSI systems to decrease the occurrence of CWH. In this research, water and aqueous sugar solutions of various concentrations were heated under a variety of operating conditions. A relationship between the thermodynamic ratio and the Peclet number was established that could effectively predict a CWH event.

The thermodynamic ratio (R_T) is a dimensionless number that was first identified by Block et al. (1977) in the research of water hammer in steam power generators. The simplified expression for thermodynamic ratio, which assumes that heat transfer from the steam to the product is 100% efficient and that the mass of the steam added to the product is negligible is:

$$R_T = \frac{T_{sat} - T_i}{T_f - T_i} \qquad \text{Equation 1}$$

where T_{sat} is the saturation temperature of the product (K), T_i is the initial product temperature (K), and T_f is the final product temperature at the onset of CWH (K).

The Peclet number (Pe) is a dimensionless heat transfer parameter, named for Jean Claude Eugene Peclet (1793-1857), that gives the ratio of bulk heat transfer to conductive heat transfer (Incropera and De Witt, 1985). It is defined by Equation 2.

$$Pe = \frac{uL}{\alpha} \qquad \text{Equation 2}$$

where u is the product velocity (ms^{-1}), L is the characteristic length of the flow geometry (m), and α is the thermal diffusivity of the product (m^2s^{-1}).

Bowser, et al. found that CWH would be avoided 90% of the time if the thermodynamic ratio could be maintained above a given value as shown in Equation 3.

$$R_T > 1.5 \times (2.4 \times 10^{-5} Pe + 1.25) \qquad \text{Equation 3}$$

Objectives of Research

The overall goal of this research was to develop a greater understanding of the safe operating conditions for a DSI heater. Two specific objectives for accomplishing this goal were:

1. To evaluate the validity and limitations of the equation developed by Bowser et al. (2003), which were based on tests with water and sugar solution, to additional liquid food products.
2. To investigate if another correlation between the physical properties of liquid food products and the temperature at which CWH occurs could be developed using common heat transfer and fluid flow parameters. This investigation was meant to be a general screening of parameters using the available data, not a focused study of any particular parameter.

CHAPTER III

RESEARCH METHODOLOGY

Products Tested

Products were selected to both reflect the previous tests of Bowser et al. (2003) and to study the effects of CWH on products with a wider range of rheological properties. First, water was tested in order to benchmark the system performance. Second, aqueous sugar solutions at concentrations ranging from 49.2 to 68.3 degrees brix were tested. Sugar solution was the product used by Bowser, et al., so it provided a standard of comparison to ensure that research and calculation methodologies of this study produced similar results as the previous research did. Third, concentrated beef bone stock (CJ NutraCon, Guymon, OK), a highly viscous paste composed of approximately 42% water, 29% protein, 20% fat, and 9% ash, was tested. This product was chosen for its rheological properties: the viscosity decreases greatly with heating. Finally, a corn starch slurry was selected for testing because of its widespread use in the food processing industry. Corn starch test samples were made by combining Pure Food Powder (Tate and Lyle - AE Staley Manufacturing Company, Decatur, IL), which is approximately 90% carbohydrate and 10% water, with water and heating to the gelatinization temperature of 160°F in a continuous-stir steam jacketed kettle. Without gelatinization, the starch and water mix is simply a solution that has physical properties similar to water, but gelatinizing the starch forms a highly viscous material.

Experimental Setup

Testing was performed at the Food and Agricultural Products Center (FAPC) at Oklahoma State University using an approach similar to that of Bowser et al. (2003). A schematic of the system is shown in Figure 4. Steam, supplied from the boiler at 414 kPa (60 psi), was conditioned by a steam separator and a carbon filter before entering the pilot scale steam injection heater (Pick Heaters, West Bend, WI Model SC2-3). For tests involving sugar water, beef broth, and corn starch, the product was stored in a stainless steal sanitary tank and was supplied to the heater using a positive displacement pump (Waukesha Cherry-Burrell, Delavan, WI, Model 15). After heating, the product was returned to a separate tank to await further testing or disposal. This setup was modified slightly for tests in which water was heated. Because the pump's hot-clearance rotors experienced slippage for water, the pump shown in Figure 4 was not used. Instead, a potable water supply was connected directly to the steam injection heater's inlet, and the heated water was discharged directly to a floor drain.

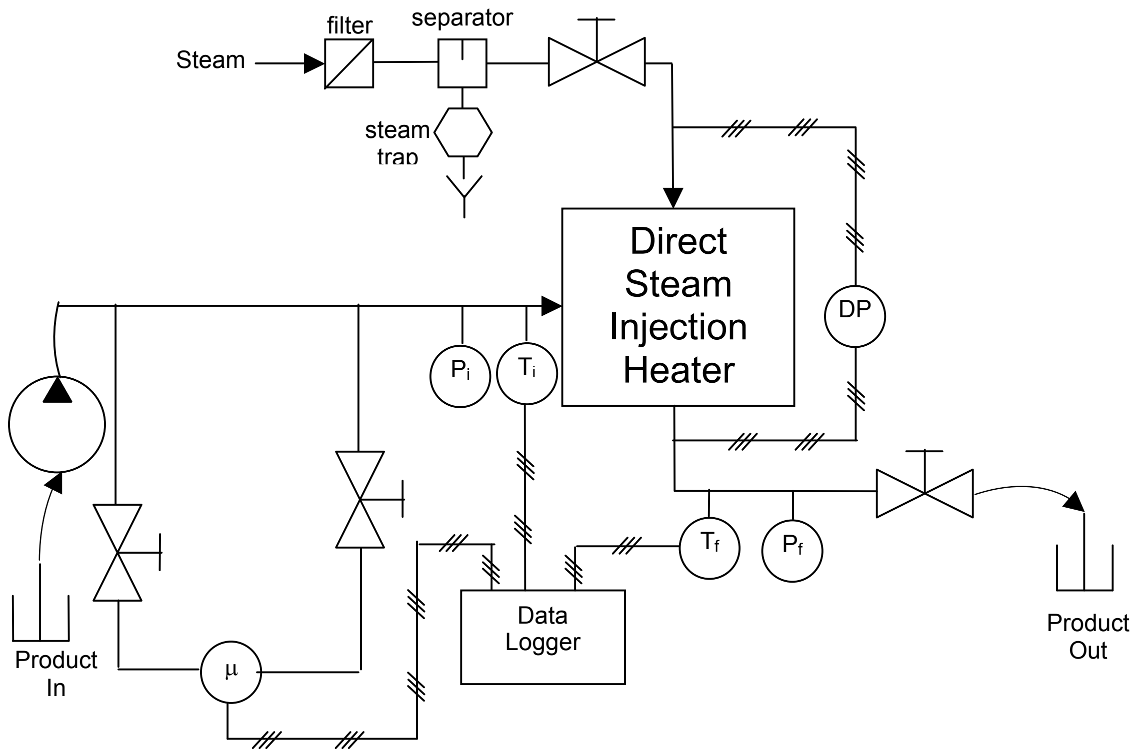

Figure 4: Experimental setup

Data Collection

To evaluate Bowser's equation, the variables used to calculate the Peclet number and the thermodynamic ratio needed to be quantified. For Equation 1 these variables were T_i, T_f, and T_{sat}; for Equation 2 the variables were L, u, and α. The method used to determine each of these variables is outlined below.

The characteristic length (L) is simply defined in textbooks as the inside diameter of the pipe for indirect heat transfer systems. However, in the DSI system tested, the product did not flow through an open pipe. Rather it flowed through the annular section between the heater body and the injector tube from which pressurized steam emanated. Therefore, the characteristic length was defined as the hydraulic diameter.

The product velocity (u) was determined by two different methods. For the experiments with water, a catch-can test using a stopwatch and scale was used to calculate the flow rate from which velocity was calculated. For all other tests, the pump calibration curve (Appendix A) was used to determine product flow rate. To convert this flow rate into a velocity, it was divided by the flow area. It was assumed that the flow area was the annular space between the injector tube and the heater housing.

The thermal diffusivities (α) of the products were calculated based on the composition of the product using Equation 4.

$$\alpha = \sum_{i=1}^{n} \alpha_i X_i \qquad \text{Equation 4}$$

where n is the number of components, α_i is the thermal diffusivity of the ith component, and X_i is the mass fraction of the ith component (Singh and Heldman, 2001). Details of these calculations and a table of thermal diffusivity values used are given in Appendix B.

T_i and T_f were both measured using sanitary resistive thermal devices (RTD) (Anderson Instruments, Fulton, NY Model SA510040370000). These values were then recorded using a digital data logger (Fluke, Everett, WA Model 2635A).

To find the saturation temperature of the product, the saturation temperature of pure water at the operating pressure was calculated using the psychometric data published by the American Society of Agricultural Engineers (ASAE, 1999), which is defined by the relationship in Equation 5.

$$T = \sum_{i-0}^{i-8} A_i \left[\ln\left(10P_s\right)\right]^i \qquad \text{Equation 5}$$

where A_0 through A_8 are constants found in Table 1 and P_s is the system operating pressure (psi).

Table 1: Constants for use in determining the saturation temperature of water (Equation 5).

Constant	Value
A0	35.1579
A1	24.5926
A2	2.11821
A3	-0.341447
A4	0.157416
A5	-0.0313296
A6	0.00386583
A7	-0.000249018
A8	6.84016E-06

To account for the effect of solutes, a boiling point rise value was then added to the saturation temperature of water to find the saturation temperature of the product at the system pressure. The boiling point rise of the sugar solutions was found in Hoynak and Bollenback (1966). For the beef bone stock and starch, the boiling point rise was determined using Duhring's rule based on the salt content of the product.

In order to perform a boiling point rise calculation, the system pressure had to be monitored and recorded. The pressure of the product both before and after the heater was monitored using sanitary pressure sensors (Anderson Instruments, Fulton, NY Model SR032C004G1105). In addition to facilitating an accurate calculation of T_{sat}, monitoring the system pressure was the primary method for determining when a CWH event occurred.

Because the purpose of this research was not only to examine the results of the research of Bowser et al. (2003), but to evaluate alternative relationships between food product properties and CWH, it was desired to know the viscosity of the product immediately prior to heating. The viscosity of water varied with temperature and was found from Table A.4.1 of Singh and Heldman (2001). For tests involving sugar water, literature sources were used to relate the Brix value with viscosity (ICUMSA, 1979). For both beef broth and corn starch, viscosity was measured using a Brookfield in-line viscometer (Brookfield Engineering, Middleboro, MD Model TT100).

Testing Procedures

In general, the following steps were taken in conducting the tests.

1. The product supply valve was opened allowing product to flow through the entire system, purging any air or water in the system. The unheated product was not recirculated during this step, but was sent directly to the outflow tank for potential use in additional tests.
2. Product flow rate was set and system pressure was controlled using a gate valve that was placed after the steam injection heater.
3. The steam valve controller was opened rapidly to 30% (previous tests correlating controller settings to steam pressure out of the valve showed that prior to 30%, the valve was not actually open). From this value, the controller was slowly opened (approximately 1% every 30 seconds) while the system was observed for signs of CWH.

4. When a CWH event was observed the approximate system pressure and outlet product temperature were recorded. These recorded values were considered as approximate, because as the system approached CWH, the system pressure, inlet product temperature, and outlet product temperature all fluctuated.
5. After recording these values, the steam valve was closed and the system parameters were reset for the next test. In some instances, the valve was merely closed enough for the CWH to cease, and then was reopened to collect another data point using the same system parameters.

System pressure fluctuations greater than 41.4 kPa (6 psi), were used as a qualitative indicator to establish the occurrence of CWH. However, other indicators such as loud noise and movement of system piping were also observed.

When testing beef broth and starch, some modifications were made to the procedure outlined above. First, in order to conserve product, the steam controller value was increased to 30% while the product was pumped at a very low flow rate, then the flow rate was increased to the test value and the steam controller setting was increased at a rate of 1% every 10 seconds until initial system pressure fluctuations of 13.8 kPa (2 psi) were observed at which time the rate of controller increase was slowed to the standard 1% every 30 seconds. The second modification was in the regulation of system pressure to maintain steady state operating conditions. The system pressure dropped significantly during testing of beef stock due to the decreased viscosity of the heated product.

This decrease in viscosity was not quantified, but was detected visually. During tests with starch, the system pressure increased. To maintain a steady system pressure during tests with both beef stock and starch, the gate valve was periodically adjusted during the test. When initial indications of CWH were observed, the researcher stopped adjusting the valve so that the final indication of a 41.1 kPa (6 psi) fluctuation in system pressure would not be affected.

After testing, the observed final temperature was compared to the temperatures recorded by the data logger and refined. This refinement was required because of the inherent instability of the output temperature during a CWH event. The final temperature may have oscillated at the moment it was observed, and therefore may not have accurately reflected the final temperature that should be used in calculating the threshold R_T value. The following method was used to hone the estimate of final temperature.

1. Fluctuations in the logged outlet temperatures were assumed to correspond to the large pressure fluctuations used to define a CWH event.
2. If the observed final temperature value was logged at the beginning of a drop in the recorded temperature, it was used as the final temperature for calculations.
3. If temperature drops occurred immediately (within 30 seconds – the time between increases in the steam valve opening) prior to the observed final temperature, it was assumed that the temperature was observed during an oscillation. A revised final temperature that corresponded to the

highest temperature reached prior to the oscillations within that time period was used.

The recorded temperature values shown in Figure 5 for test 12 of beef stock are used to illustrate this method. The observed final temperature for this test was 70 °C. Because there were temperature fluctuations that preceded this value, step 3 was used to revise the final temperature. There were two drops in temperature that occurred within the 30 seconds prior to the observed value. The highest temperature before either of these drops was 63 °C, which was used as the final temperature in calculations.

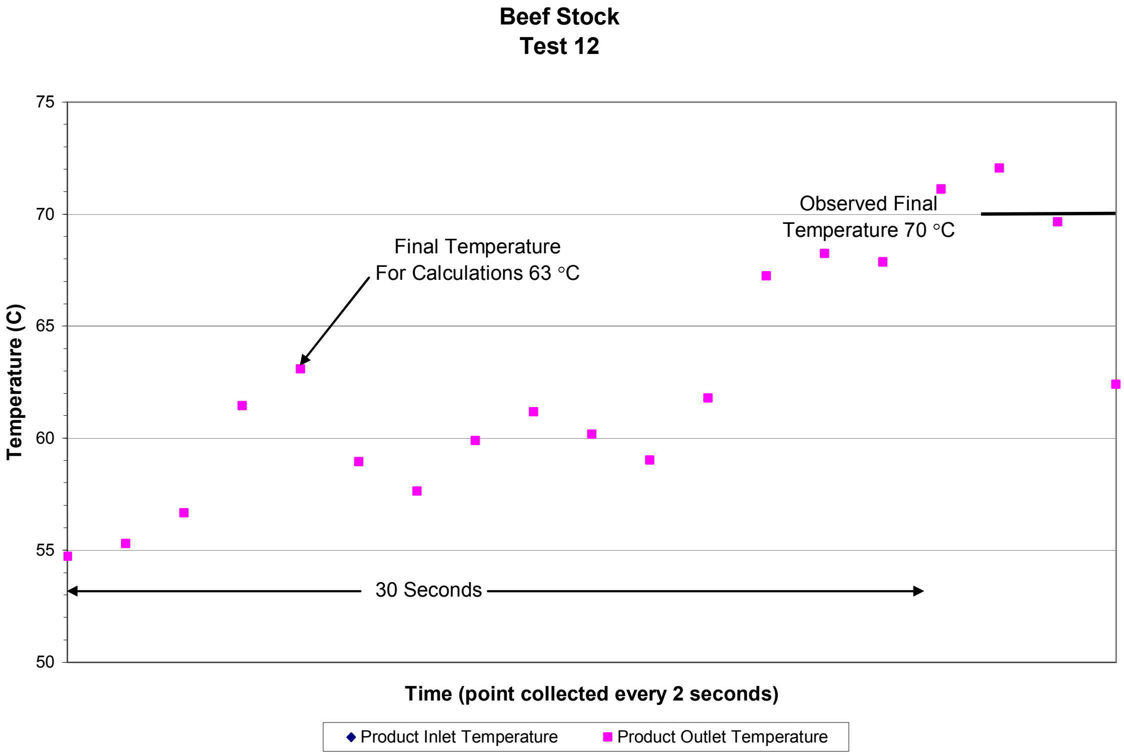

Figure 5: Example of determination of T_f based on temperatures recorded by the data logger.

The final step in the research process was to calculate dimensionless parameters that could potentially be used to predict CWH. First, the thermodynamic ratio and Peclet number were calculated for each test for use in comparing to the predictive equation developed by Bowser, et al. Second, five additional dimensionless parameters: the Reynolds, Prandtl, Nusselt, Stanton, and the Jacob numbers were calculated for use in the screening investigation.

The Reynolds number, defined by Equation 6, described the flow characteristics of the product.

$$\mathrm{Re} = \frac{\rho V L}{\mu} \qquad \text{Equation 6}$$

where ρ is product density (kgm^{-3}), V is product velocity (ms^{-1}), L is the characteristic length (m), and μ is product viscosity (c_P). This parameter can also be described as a ratio of the inertial forces of the fluid to the viscous forces of the fluid (Incropera and De Witt, 1985). When Re is less than 2100 the flow is classified as laminar, when it is between 2100 and 4000 the flow is considered transitional, and when Re is greater than 4000 the flow is turbulent (Singh and Heldman, 2001). This parameter impacts steam injection heating, because as when the Reynolds number increases, more mixing occurs in the fluid, which should help to incorporate the steam into the product, reducing the opportunity for CWH to occur.

The Prandtl number is a ratio of the molecular diffusivity of momentum to the molecular diffusivity of heat for forced convection (Incropera and De Witt, 1985). It is defined as:

$$\mathrm{Pr} = \frac{\mu c_p}{k} \qquad \text{Equation 7}$$

where μ is the viscosity (cP), c_p is the specific heat ($kJkg^{-1}C^{-1}$), and k is the thermal conductivity ($Wm^{-2}C^{-1}$).

The Nusselt number relates the rate of heat transfer due to convection to the rate of heat transfer due to conduction (Incropera and De Witt, 1985). It is defined as:

$$\mathrm{Nu} = \frac{\mathrm{hd_c}}{\mathrm{k}} \qquad \text{Equation 8}$$

where h is the convective heat transfer coefficient ($Wm^{-2}C^{-1}$), d_c is the characteristic dimension (m), and k is the thermal conductivity ($Wm^{-1}C^{-1}$). The value of Nu relates to the magnitude by which convection increases the amount of heat transferred, so a Nusselt value of 3 means that the heat transfer due to convection is 3 times the amount due solely to conduction (Singh and Heldman, 2001).

The Nusselt number is intended to be used to describe indirect heat transfer, but DSI heating does not employee a heat transfer surface. An attempt to account for this difference was made by using Equation 9 found in the work of Goodykoontz and Dorshe (1966) to quantify the convective heat transfer component of the Nusselt number.

$$h = \frac{q_i}{t_{vs} - t_{iw}} \qquad \text{Equation 9}$$

where q_i is the heat flux (Wm^{-2}) based on the heat flux area calculated using the pipe inside diameter, t_{vs} is the saturation temperature of the steam (C), and t_{iw} is the initial temperature of the wall (C). Goodykoontz and Dorshe applied this equation to film condensation, but it was assumed in this research to also be applicable to droplet condensation.

The Stanton number simply relates the previous three coefficients (Incropera and De Witt, 1985).

$$St = \frac{\mathrm{Nu}\,\mathrm{Re}}{\mathrm{Pr}} \qquad \text{Equation 10}$$

Finally, the Jacob number was calculated using Equation 11.

$$Ja = \frac{\rho_L c_{pL} (T_{sat} - T_\infty)}{\rho_G h_{LG}} \qquad \text{Equation 11}$$

where ρ_L is the density of the liquid (kgm^{-3}), c_{pL} is the specific heat of the liquid (m^{2}s^{-2}K^{-1}), T_{sat} is the saturation temperature of the steam (°C), T_∞ is the liquid temperature (°C), ρ_G is the density of the gas (kgm^{-3}), and h_{LG} is the enthalpy of evaporation (m^{2}s^{-2}). The Jacob number is part of a theoretical model that is used to describe heat transfer in bubble type condensers based on transient conduction (Hewitt et al., 1994).

CHAPTER IV

ERROR ANALYSIS

All measurable quantities are subject to error - the difference between the measured value and the true value of the parameter. The two main contributors to error are instrumental error and methodological error.

Instrumental Error

Instrumental error is due to the cumulative effects of imperfections in the measuring equipment and human imprecision in reading the measurement (Bevington, 1969). In the error analysis for this research, human imprecision from reading the value off of the instrument was considered insignificant, because all of the sensors used were digital (Rabinovich, 2000). The instrument's accuracy, which quantifies the inherent error associated with it, was found in the literature that accompanied each instrument. Another aspect of the instrumental error is the number of significant digits to which an instrument is read, referred to as data collection precision. The contributions to the error for the DSI system tested are shown in Table 2. The larger of the two values, instrument accuracy and data collection precision, was the observational uncertainty for that instrument. Another contribution to the uncertainty associated with the instrumentation was the assumption that each instrument used was properly calibrated, the viscometer at the factory and the pressure and temperature sensors during previous research. This assumption was correct for the viscometer, but incorrect for the temperature and pressure sensors, adding an unknown error to the data.

Table 2:Measurement Error

Instrument	Property Measured	Instrument Accuracy	Data Collection Precision
RTD	$T_{p,I}$ & $T_{p,f}$	0.66 C	0.01
Analog transmitter	N/A	±0.18 C	N/A
Data logger-Temperature	N/A	±0.10 C	N/A
Viscometer	Viscosity	20cP	0.01cP
Data logger-Viscosity	N/A	±0.5cp	N/A
Pump	Flow rate	0.11 gpm	N/A

Methodological Error

Methodological error is due to human imprecision in selecting the correct value of the measured parameter. In this research there were methodological errors associated with the final temperature values and the characteristic length.

The error associated with selecting the T_f value used in calculations was based on the range of temperature values in the oscillations surrounding the selected final temperature, resulting in a methodological error of 5 °C for T_f. The method and results of this assessment are provided in Appendix D.

The characteristic length also has methodological error associated with it. This is due to the ambiguity in the definition of L for DSI heaters. This error was defined as the difference between the two possible values of L, the hydraulic radius and the hydraulic diameter, which has a value of 0.0255 m.

Model Error

Errors in the determination of variable values are consequential when considering the validity of a model. For this reason, the technique presented by Doebelin (1966) was used to find the absolute error of the model presented by Bowser et. al (2003) for the instruments and techniques used in this analysis. This techniques says that, if a model's output depends on multiple input variables (Equation 12), then the absolute error of the model output is proportional to the errors of each variable (Doebelin, 1966). In other words, the error in N is approximately the error in a variable multiplied by the effect that the variable has on the final value of N, summed for all variables in the model (Bevington, 1969). This concept can be expressed mathematically using the Taylor series expansion in Equation 13. The higher-order terms in Taylor's expansion are neglected, because all of the individual errors are small (Bevington, 1969).

$$N = f(u_1, u_2, u_3 ... u_i) \qquad \text{Equation 12}$$

where N is the model output and the u_i's are the model input variables.

$$E(N) = \left|\Delta u_1\left(\frac{\delta N}{\delta u_1}\right)\right| + \left|\Delta u_2\left(\frac{\delta N}{\delta u_2}\right)\right| + \left|\Delta u_3\left(\frac{\delta N}{\delta u_3}\right)\right| + ... + \left|\Delta u_i\left(\frac{\delta N}{\delta u_i}\right)\right| \qquad \text{Equation 13}$$

Since the original goal of this research was to examine the applicability of the equation developed by Bowser et al. (2003), the model error will be examined by applying Equation 13 to Equations 1 and 2, the result of which is given in Equations 14 and 15.

$$E(R_T) = \left|\Delta u_{T_{p,sat}}\left(\frac{\delta R_T}{\delta u_{T_{p,sat}}}\right)\right| + \left|\Delta u_{T_{p,i}}\left(\frac{\delta R_T}{\delta u_{T_{p,i}}}\right)\right| + \left|\Delta u_{T_{p,f}}\left(\frac{\delta R_T}{\delta u_{T_{p,f}}}\right)\right| \qquad \text{Equation 14}$$

$$E(Pe) = \left|\Delta u_u \left(\frac{\delta Pe}{\delta u_u}\right)\right| + \left|\Delta u_L \left(\frac{\delta Pe}{\delta u_L}\right)\right| + \left|\Delta u_\alpha \left(\frac{\delta Pe}{\delta u_\alpha}\right)\right|$$ Equation 15

The partial derivates for use in Equations 14 and 15 are calculated in Equations 16-19.

$$\frac{\delta Pe}{\delta u_u} = \frac{L}{\alpha}$$ Equation 16

$$\frac{\delta Pe}{\delta u_L} = \frac{u}{\alpha}$$ Equation 17

$$\frac{\delta R_T}{\delta u_{T_{p,i}}} = \frac{T_{p,sat} + T_{p,f}}{(T_{p,f} - T_{p,i})^2}$$ Equation 18

$$\frac{\delta R_T}{\delta u_{p,f}} = \frac{T_{p,in} - T_{p,sat}}{(T_{p,f} - T_{p,i})^2}$$ Equation 19

By combining all of the instrumental errors and the methodological error that contribute to each variable, the variable's uncertainty can be determined. The uncertainties for each variable in the model of Bowser, et al. are given in Table 3.

Table 3: Contributions to model uncertainty

Variable	Contributions to Uncertainty	Variable Uncertainty
velocity, u	pump calibration curve error	0.0063 ms^{-1}
characteristic length, L	multiple definitions that can be applied to a single variable	0.0255 m
thermal diffusivity, α	Insignificant	
initial product temperature, T_i	RTD, analog transmitter, data logger	1.22 C
final product temperature, T_f	RTD, analog transmitter, data logger, methodological error	6.22 C
product saturation temperature, T_{sat}	Insignificant	

Substituting these uncertainty values and the partial derivatives in Equations 18-19 into Equation 14 gives an average error in thermodynamic ratio of 0.75.

CHAPTER V

RESULTS AND DISCUSSION

The first objective of the research was to evaluate the applicability of the equation developed by Bowser et al. (2003), based on tests with water and sugar solution, to additional liquid food products. This equation stated that CWH would be avoided 90% of the time if

$$R_T > 1.5 \times (2.4 \times 10^{-5} Pe + 1.25) \qquad \text{Equation 3}$$

A total of 41 individual test runs were conducted during this study. For the data analysis, these results were combined with data collected from 24 tests that were conducted by Bowser, et al. (2003). Of the 65 test runs, 14 were water, 23 were sugar solution, 22 were beef stock, and 6 were corn starch slurry. It would have been desirable to have a larger number of data points over a wider range of conditions for the corn starch; however, samples were limited due to time constraints. The system parameters that could be varied for each test were the product flow rate, system pressure, initial product temperature, and product viscosity prior to heating. Table 4 shows the range of these parameters tested within this study. For each test the values of these parameters as well as the final product temperature were recorded and are provided in Appendix C.

Table 4: Range of parameters tested within the study

Product	***Flow rates gpm***	***System pressures psi***	***Initial product temperatures °C***	***Viscosities cP***
Water	0.23-3.80	14.0-35.0	13.72-21.94	0.95-1.18
Sugar Solution	0.48-2.89	10.5-33.0	15.00-43.89	7-174
Beef stock	0.96-2.41	12.0-35.0	11.75-33.72	353-3463
Starch	0.96-2.17	17.0-32.0	35.40-45.47	312-1554
All products	0.23-3.80	10.5-35.0	11.75-45.47	1-3463

The first analysis performed on the data was to determine if the system behavior with respect to CWH during each test adhered to the predictive equation of Bowser, et al. The threshold value of R_T and the Peclet number were calculated for each test run (see Appendix E for calculated values). Figure 6 shows the results of tests performed using water and sugar solution, the products used in the development of the equation.

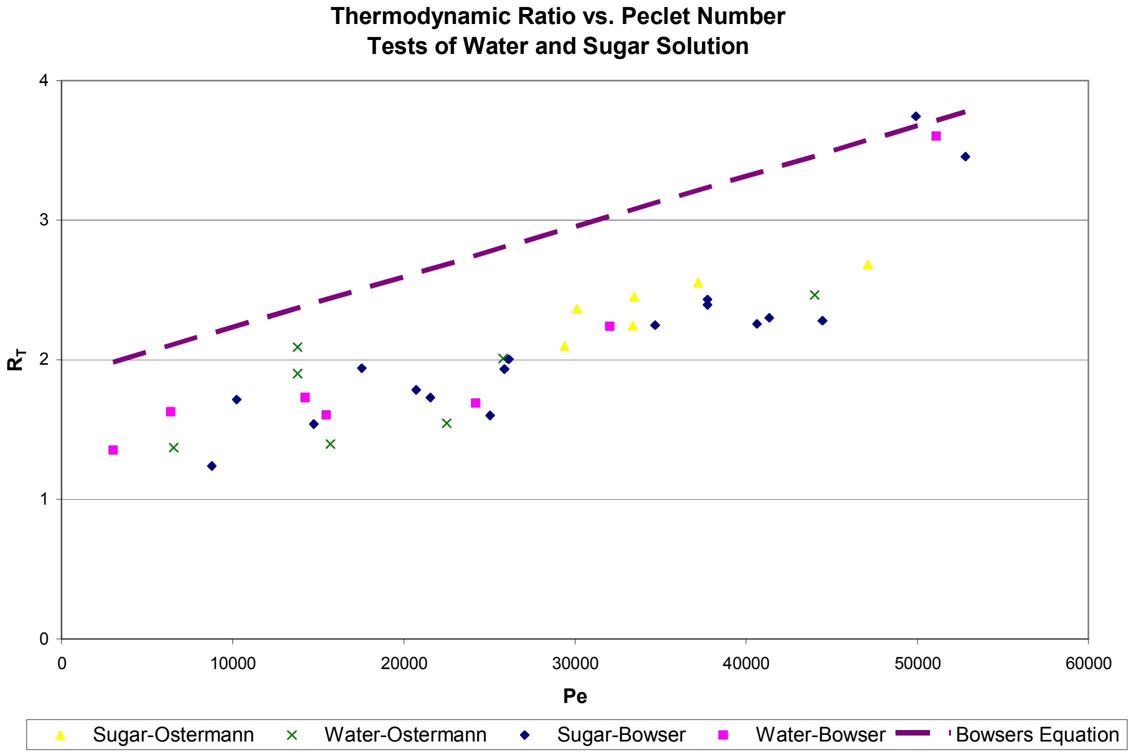

Figure 6: Analysis of test results for water and sugar solution compared to the predictive equation.

As Figure 6 shows, the data collected for water and sugar solution in this research support the predictive equation developed by Bowser, et al. Of the combined data set, CWH occurred as predicted for 100% of the water tests and 96% of the sugar solution tests.

The second analysis was to see if Bowser's equation was equally applicable to the tests with beef stock and corn starch. The results of this analysis are shown in Figure 7 and presented in Table 5. It may be observed from Figure 7 that the data is not spread evenly across the range of Pe numbers. This was due to varying inputs of pressure, initial temperature, and flow rate randomly without designing the experiments to target specific Pe values. In addition, redundant experiments (shown in example areas A, B, and C enclosed in dashed lines in Figure 7) resulted in a wider than expected range of Rt values as indicated by error bars that did not overlap. This indicated that some experimental error or other factor was present that was not accounted for in the error analysis. This error could be from many sources including the calculation of the products' physical properties, the regulation of pressure during testing, uncalibrated sensors, or heater inefficiency due to improper cleaning. An improved approach to data collection is given in the Conclusions section.

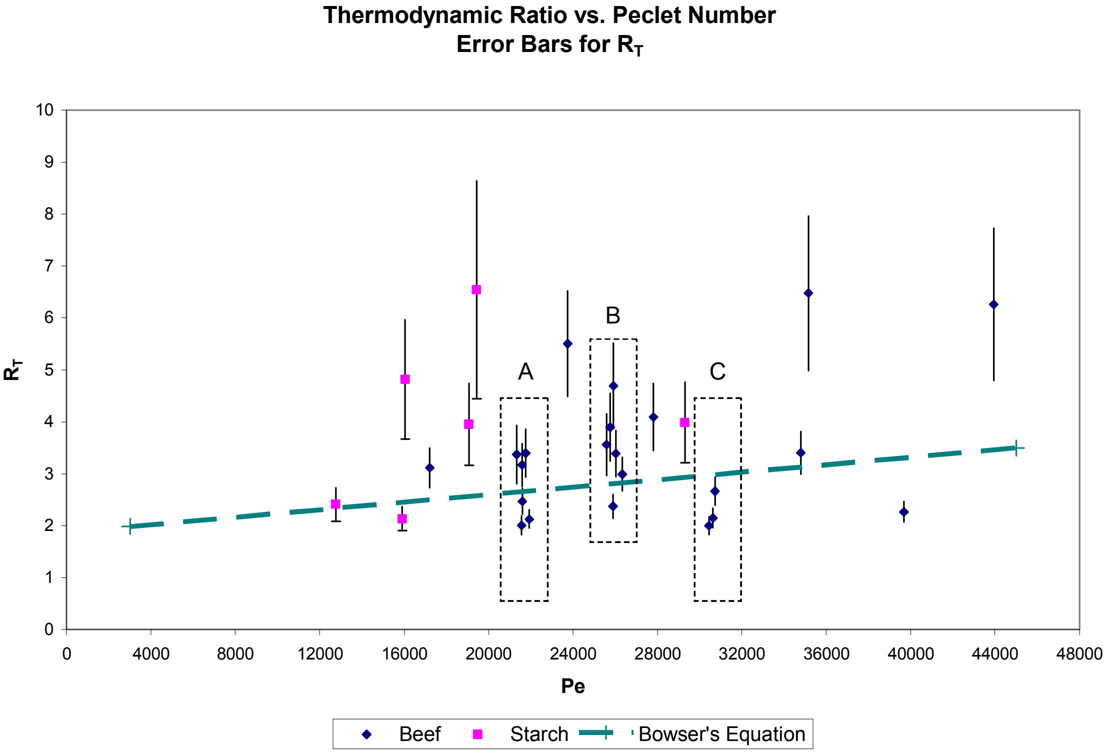

Figure 7: Comparison of results of tests of beef stock and starch to the predictive equation.

Table 5: Adherence to predictive equation based on product

Product	***Test Runs***	***Occurrences of CWH***	***Percentage of Tests that Adhere to the Predictive Equation***
Water	14	0	100%
Sugar Solution	23	1	96%
Beef Stock	22	14	36%
Starch	6	5	17%
All Products	65	20	69%

Because the behavior of the system when testing beef stock and starch did not appear to follow the predictive equation, data analysis was conducted for the final objective of this research: to investigate if another correlation between the physical properties of liquid food products and the temperature at which CWH occurs could be developed using common heat transfer and fluid flow dimensionless parameters. As previously stated, the parameters that were selected for examination were the Reynolds, Prandtl, Nusselt, Stanton, and the Jacob numbers. The values of these parameters for each test are provided in Appendix E, and Table 6 shows the minimum, maximum, average and standard deviation of each of the dimensionless parameters tested.

Table 6: Descriptive statistics of dimensionless parameters tested.

	Maximum	***Minimum***	***Average***	***Standard Deviation***
Thermodynamic Ratio	6.54	1.24	2.72	1.22
Peclet Number	52815.79	3016.69	26479.02	11395
Prandtl Number	27037.22	6.54	5304.72	7559.97
Reynolds Number	7605.12	0.89	679.75	1444.15
Nusselt Number	17147.70	1901.84	9043.62	3878.49
Stanton Number	1.44E+07	1.69E-01	9.48E+05	2.64E+06
Jacob Number	95.98	62.49	78.03	9.03

Because the purpose in developing a predictive equation is to provide operators with a simple guideline for setting the operating temperature of steam injection heaters, the first analysis that was performed for this objective was to see if a relationship could be defined using only linear regression to relate the thermodynamic ratio to each of the dimensionless parameters. Figures 8-12 show the linear relationship between the thermodynamic ratio and each of the dimensionless parameters studied.

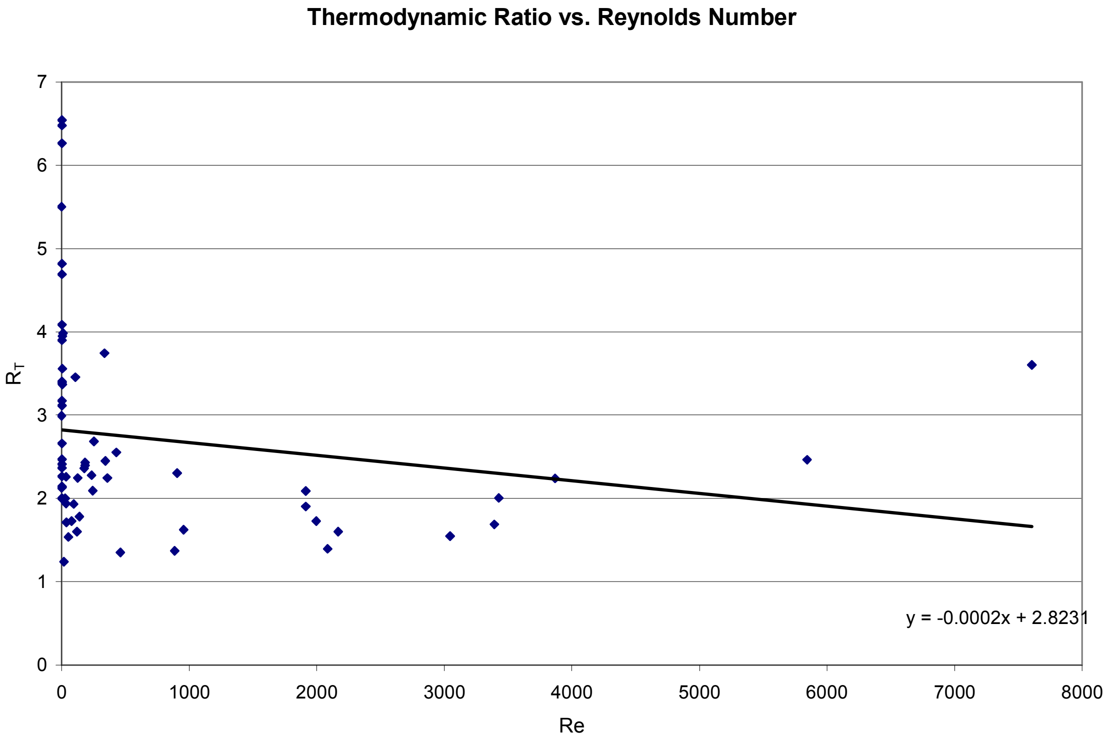

Figure 8: Linear regression of the relationship between thermodynamic ratio and Reynolds number.

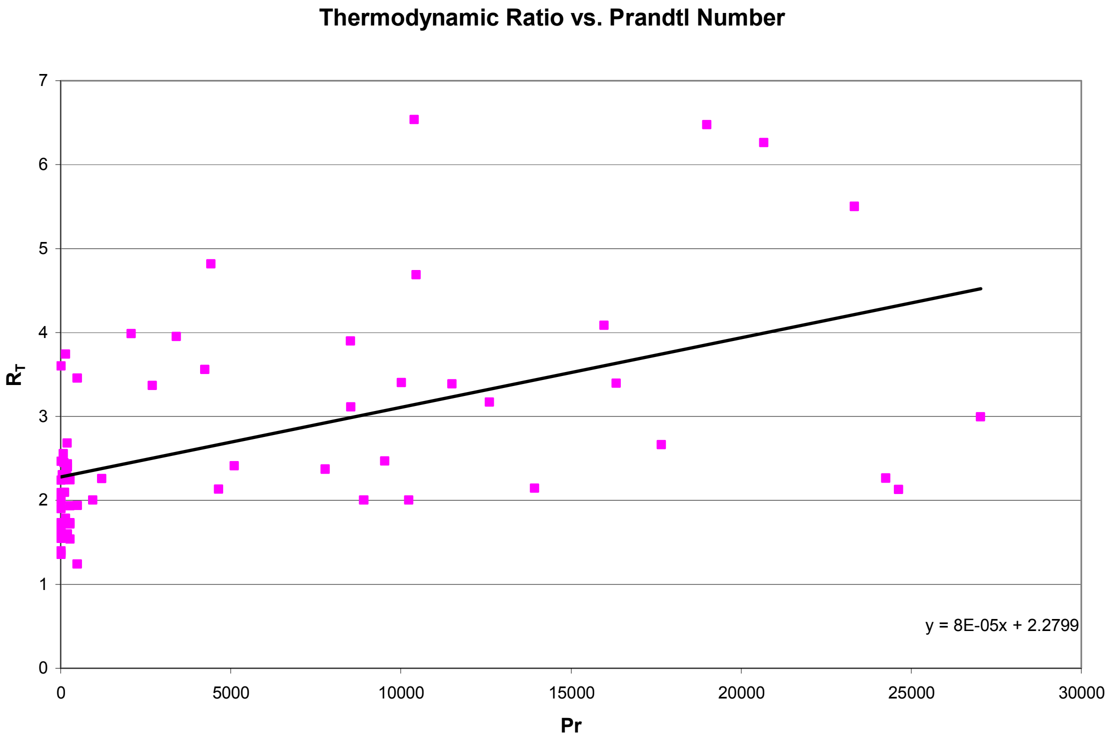

Figure 9: Linear regression of the relationship between thermodynamic ratio and Prandtl number.

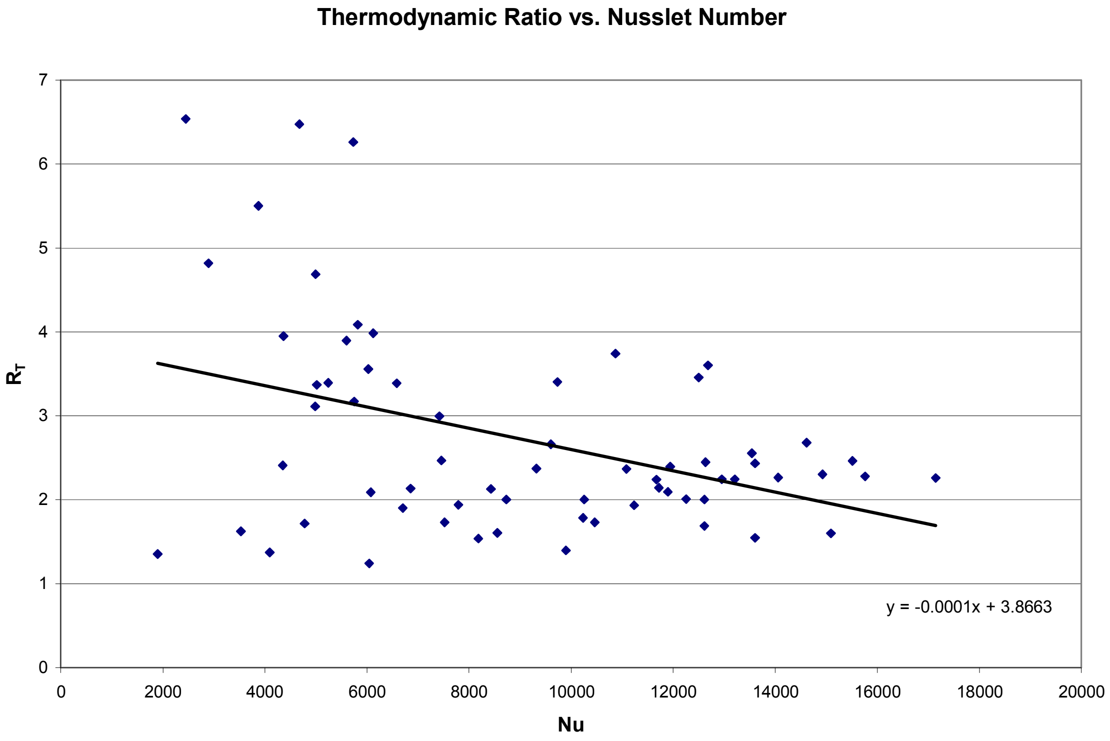

Figure 10: Linear regression of the relationship between thermodynamic ratio and Nusselt number.

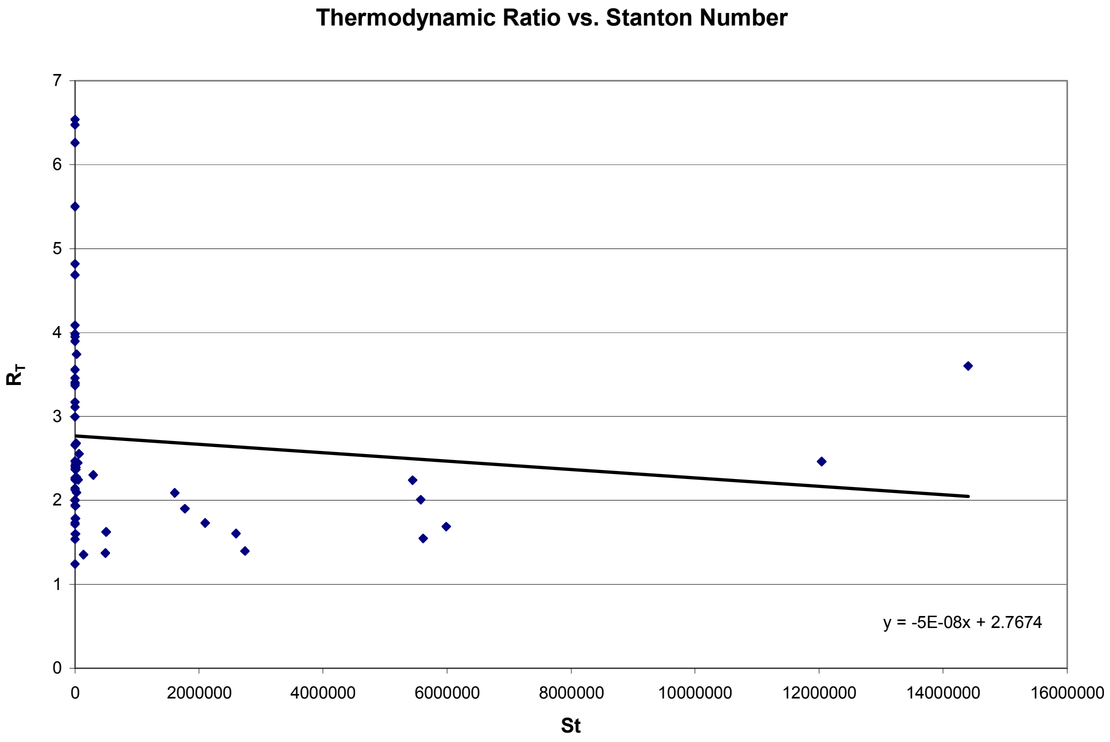

Figure 11: Linear regression of the relationship between thermodynamic ratio and Stanton number.

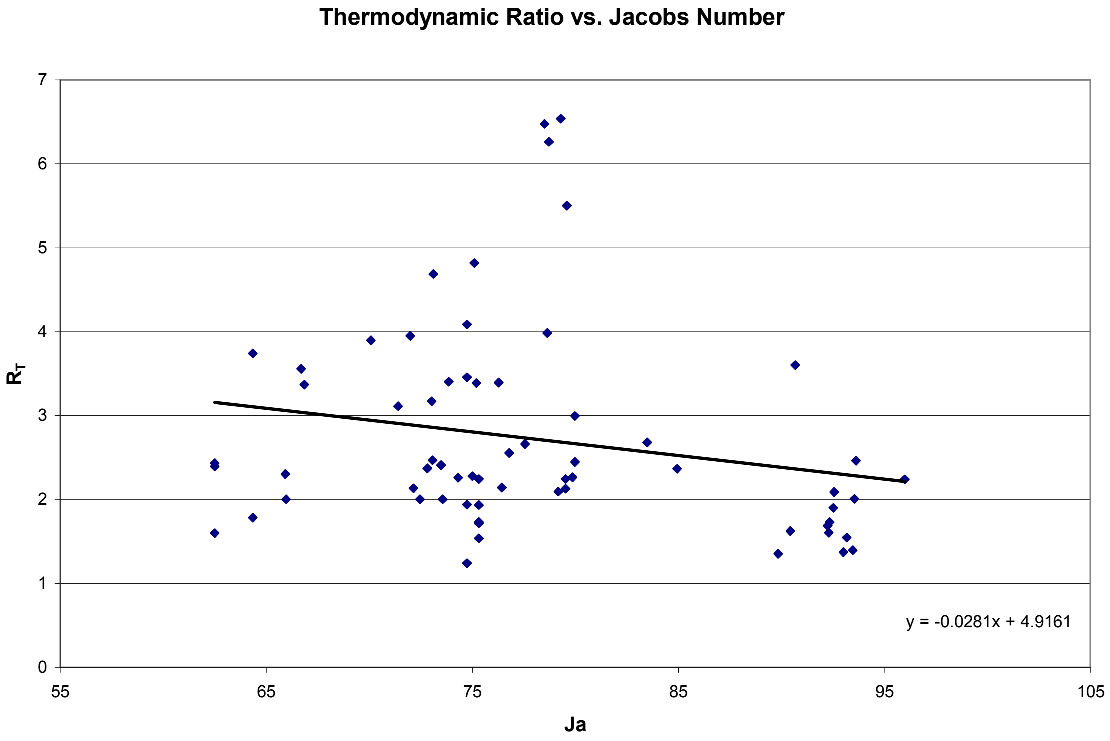

Figure 12: Linear regression of the relationship between thermodynamic ratio and Jacobs number.

As previously mentioned, the research was not properly designed to ensure a broad range of data points across all dimensionless parameters, resulting in redundant data. To reduce the influence of this redundancy, a second analysis was performed. For this investigation, all data points were grouped by R_T value (based on tenths). For each group, both the R_T and the dimensionless parameter values were averaged. The results of this data manipulation are shown in Table 7. These relationships were then graphed, the results of which are provided in Appendix F.

Table 7: Averaged R_T and dimensionless parameter values for data analysis.

R_T	*Pe*	*Pr*	*Re*	*Nu*	*St*	*Ja*
1.24	8772.17	488.55	17.93	6044.19	2.22E+02	74.75
1.36	4786.00	6.96	674.26	3000.31	3.14E+05	91.43
1.40	15706.79	7.53	2086.15	9902.69	2.74E+06	93.46
1.54	18614.43	141.36	1549.04	10892.65	2.81E+06	84.24
1.63	17773.87	56.40	1660.01	9949.28	2.27E+06	84.37
1.74	16688.95	176.39	562.95	8252.31	5.29E+05	76.83
1.92	19067.73	257.04	681.72	8577.38	5.94E+05	80.86
2.02	23549.02	4018.14	1075.07	9985.53	1.44E+06	79.62
2.12	24464.12	10832.06	62.64	9724.12	6.02E+03	76.82
2.26	37470.16	4335.44	770.57	14133.92	9.20E+05	80.00
2.36	33777.12	2050.59	317.46	11819.07	7.95E+04	71.54
2.44	29910.78	2988.80	1275.71	10711.88	2.42E+06	76.53
2.55	37190.94	86.58	429.43	13543.86	6.72E+04	76.78
2.67	38918.62	8917.68	127.46	12108.62	9.95E+03	80.52
2.99	26334.43	27037.22	0.97	7421.43	2.67E-01	79.98
3.14	19404.06	10568.35	1.87	5369.20	9.82E-01	72.22
3.38	23683.37	7093.64	5.09	5803.94	8.04E+00	71.02
3.42	36451.86	8945.30	37.59	9158.13	9.22E+02	74.97
3.56	25592.47	4235.09	6.04	6025.86	8.59E+00	66.70
3.60	51099.48	6.70	7605.12	12680.30	1.44E+07	90.68
3.74	49912.64	147.73	337.48	10868.05	2.48E+04	64.35
3.94	24717.58	4666.30	7.57	5361.60	1.69E+01	73.57
4.09	27815.18	15970.11	1.74	5820.41	6.34E-01	74.74
4.69	25915.86	10453.41	2.48	4993.05	1.18E+00	73.12
4.82	16042.30	4419.19	3.63	2891.87	2.38E+00	75.10
5.50	23750.62	23327.16	1.02	3874.04	1.69E-01	79.58
6.26	43935.66	20677.57	2.13	5733.39	5.90E-01	78.72
6.48	35165.19	18991.48	1.85	4678.95	4.56E-01	78.49
6.54	19442.14	10387.40	1.91	2446.76	4.50E-01	79.30

The third step in the data analysis was to investigate if the relationship between the thermodynamic ratio and each dimensionless parameter could be better explained using a different type of curve to define the data. For each dimensionless parameter, regression equations were defined using logarithmic, exponential, and power equations for all of the tests and for the averaged values. The graphs of this analysis are included in Appendix G.

The final step in the data analysis was to determine for each dimensionless parameter if a stronger relationship existed for a portion of the data than that of the entire data set. The segmentation of the data was done by visually inspecting the graphs of thermodynamic ratio verses each of the dimensionless parameters. Appendix H show the results of this analysis.

For each of the analyses described above, a coefficient of correlation (r^2) was determined. The r^2 value describes the percentage of the data points that can be described by the regression equation and was used in drawing conclusions about the applicability of each relationship studied. Table 8 lists all of these r^2 values.

Table 8: Coefficient of determination values for all analysis.

			Linear	*Log*	*Exponential*	*Power*
All Tests		***Pe***	0.0906	0.1140	0.1595	0.2033
		Pr	0.2620	0.3107	0.2621	0.3600
		Re	0.0321	0.2587	0.0328	0.2822
		Nu	0.1612	0.1782	0.1023	0.1063
		St	0.0117	0.3074	0.0105	0.3342
		Ja	0.0431	0.0350	0.0767	0.0657
Averaged Tests		***Pe***	0.1288	0.1618	0.2167	0.2785
		Pr	0.4111	0.3307	0.4040	0.3915
		Re	0.0395	0.5064	0.0333	0.4955
		Nu	0.2954	0.3300	0.2019	0.2240
		St	0.0149	0.5682	0.0099	0.5546
		Ja	0.0765	0.0708	0.1474	0.1402
Outliers Deleted	R_T<5	***Pe***	0.1220	0.1553	0.1910	0.2427
	Pr<500	***Pr***	0.0099	0.0444	0.0064	0.0514
	Pr>500	***Pr***	0.0386	0.0545	0.0271	0.0468
	Re<500	***Re***	0.0934	0.2139	0.0941	0.2256
	Re>500	***Re***	0.6115	0.3690	0.5539	0.3537
	R_T<5	***Nu***	0.0664	0.0596	0.0286	0.0214
	St<100,000	***St***	0.0355	0.2575	0.0243	0.2618
	St>100,000	***St***	0.5712	0.2643	0.5187	0.2770
	R_T<5	***Ja***	0.1138	0.1045	0.1329	0.1224

CHAPTER VI

SUMMARY AND CONCLUSIONS

Observations from Research

In conducting this research, the challenges of operating a DSI heater were very apparent. It was found that Schroyer's (1997) assertion, that a warm-up period is not needed because heating begins as soon as the steam valve is opened, does not truly capture the operating conditions. Instead, to start the system, product had to be flowing through the system and the steam valve had to be opened slowly. If the steam valve was opened too rapidly, CWH occurred prematurely. This startup procedure caused a substantial amount of wasted product. However, attempting to mitigate for this waste by recycling the product was not desirable because the testing required steady state conditions, and recycling product would have caused variation in both the product inflow temperature and the product inflow viscosity during testing. In addition, recycling would not have reflected a typical production situation. A second insight received was that, because some products become less viscous during heating, the system pressure can drop drastically resulting in CWH at lower than expected temperatures. Finally, it was found that using very viscous products such as the starch was also difficult. Prior to conducting tests, it was observed that the high viscosity of the starch could cause large system pressures resulting in hose blowouts upstream of the heater. These high pressures were reduced for testing by limiting the flow rate and opening the gate valve.

Conclusions from Analysis of Data

The first objective of this research was to determine the validity of the equation developed by Bowser, et al. (Equation 3) when applied to additional food products. This equation was developed using water and sugar solution, and it was found that for the new data points collected in this research using water and sugar solution, it adequately defined the threshold thermodynamic ratio for CWH. The results for beef stock and corn starch were inconclusive due to experimental error and insufficient data.

The second objective for this research was to examine if the relationship between the physical properties of a product, the system operating conditions, and the threshold R_T value could be better predicted by a different equation. Based on the coefficient of variation values shown in Table 8, the following conclusions can be made.

1. The Jacob number should not be used to develop a relationship between by which to predict safe operating conditions for a DSI system. None of the equations developed for this parameter were able to explain more than 7% of the data.
2. Power and logarithmic relationships should receive greater attention for use in defining a relationship between product physical properties, system operating conditions and the threshold thermodynamic ratio. The highest coefficient of determination for both the entire data set analysis and the

averaged data set analysis corresponded to one of these two relationships. The only exception being, the averaged analysis for Pr which had an r^2 value 0.02 higher for the linear relationship than the power relationship.

3. Further investigation should focus on the Prandtl, Reynolds, and Stanton numbers which had the highest r^2 values for both the entire data set analysis and the averaged data set analysis. In addition, the Peclet number should not be excluded from further investigation, because it is the product of the Reynolds and Prandtl numbers.
4. Based on the error analysis, the above conclusions should not be considered definitive. Not only was there an abundance of quantifiable errors, but it was also found from the results of redundant experiments that fell outside of the expected range of error, that some unknown error existed in the experimental setup and/or technique. The steps proposed in the following section should be taken to reduce model error in further research.

Recommendations for Further Research

In order to collect a more reliable data set and reduce the influence of errors, modifications must be made to the experimental setup and research techniques.

The experimental setup should be altered and improved to allow for better accuracy in determining the temperature at which CWH occurs. One way that this can be accomplished is by using the data logger to record the system pressure in addition to recording the product temperature and viscosity. This would eliminate the methodological error associated with the determination of T_f, because the first instance of 41.1 kPa (6psi) pressure fluctuation could be compared directly to the outlet temperature. In addition, all instruments should be properly calibrated immediately prior to use. Finally, equipment that monitors sound and/or vibration could be incorporated into the system setup. For this research only a quantitative criterion was used to indicate a CWH event. This criterion was pressure fluctuations of 41 kPa (6 psi), which was a lower value than the criterion of 60 kPa used by Bowser et al. (2003), because it was found that system stability was difficult to maintain up to 60 kPa. Installing sound and vibration monitors recognizes that requiring a specific value of pressure oscillation to indicate CWH may not be appropriate. It would allow qualitative indicators used by Bowser, such as shaking of system piping and gasps of collapsing steam voids, to be accounted for in a quantitative manner.

The second suggested modification is to minimize the potential for unknown errors. A potential source of unknown error was the manual regulation of the system pressure during testing of beef broth in an attempt to maintain steady state operating conditions. Figure 13 shows the recorded temperature values and the impact of the reduction in system pressure due to the change in the viscous properties of beef stock during heating. The product went from a thick sticky paste to a thin watery liquid causing the system pressure to drop, by as much as 170 kPa (25 psi). System pressure drops resulted in premature occurrence of CWH, which caused blow-outs of system hoses. Even though every effort was made to adjust the pressure as little as possible when signs of approaching CWH were observed, any adjustment would affect the reliability of the data set. A pressure regulating valve would enable the system pressure to be maintained at a steady state. In addition, a pressure relief valve and use of rigid pipes instead of flexible hoses could help prevent blow-outs.

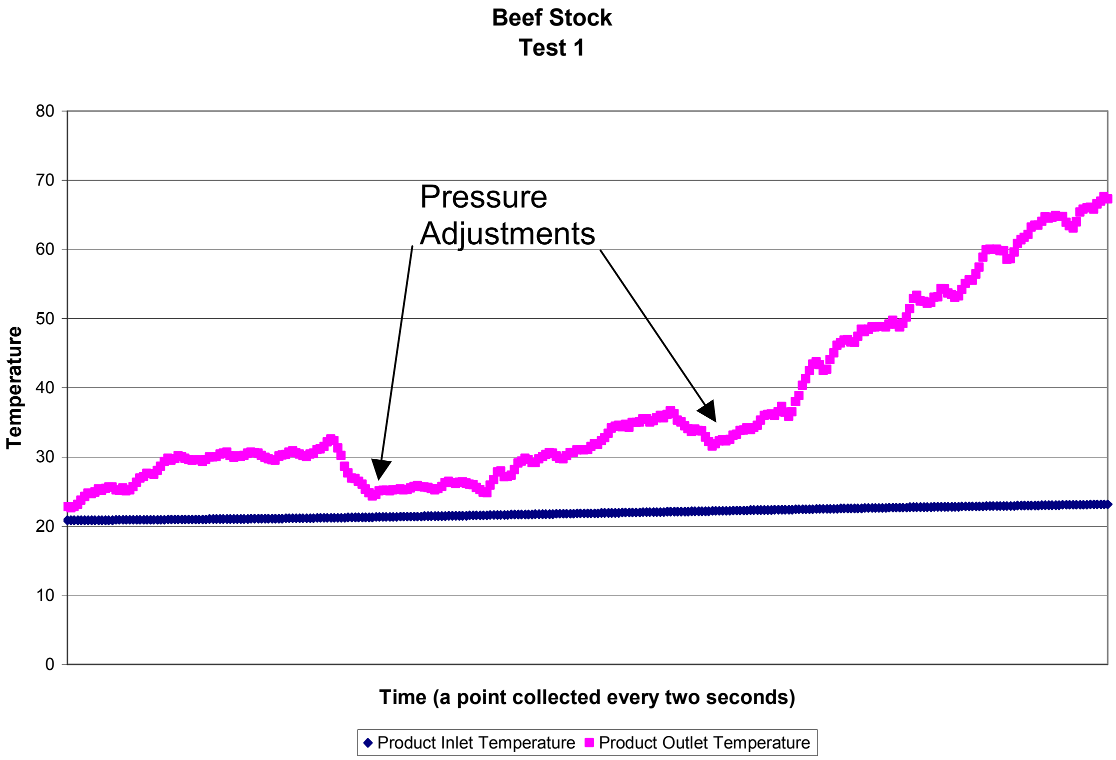

Figure 13: Data logger output of T_i and T_f over time showing system pressure adjustments during testing.

A second potential source of unknown error was the maintenance of the heater during testing. The heater was cleaned by running water through the heater until it flowed clear. However, disassembly of the heater after the research was conducted showed that this was not a sufficient cleaning method. In future research, the apparatus should be disassembled and cleaned after each round of tests and between tests on different products.

The third suggestion for future research is to develop a better understanding of how to define the characteristic length for a DSI heater. One definition of characteristic length is the hydraulic radius defined in Equation 20.

$$r_h = \frac{A}{P} \qquad \text{Equation 20}$$

where A is the cross-sectional flow area (m^2) and P is the wetted perimeter (m). Other researchers choose to use the hydraulic diameter, calculated for two concentric pipes as shown in Equation 21.

$$d_h = \frac{4\left(\frac{\pi D^2}{4} - \frac{\pi d^2}{4}\right)}{\pi D + \pi d} = D - d \qquad \text{Equation 21}$$

where D is the diameter of the exterior pipe (m) and d is the diameter of the interior pipe (m). The value of hydraulic radius for this heater was 0.0085 m and the hydraulic diameter was 0.034 m. While the hydraulic diameter was selected for use in this study, being able to characterize this value with certainty would allow for a better defined relationship for predicting safe operating conditions for a DSI heater.

Finally, it is recommended that the research techniques be modified to collect data that will define the entire spectrum of each parameter of interest. Because this research was to serve as a general screening of dimensionless parameters, an effort was not made to tailor system operating conditions to collect data for any particular parameter. If research were to progress based on these results, boundary conditions should be established for the Re, Pr, and St numbers, and data should be collected to fill in the gaps of this research. For example, more data should be collected for Reynolds numbers between 10 and 100, for Prandtl numbers between 10 and 100 as well as between 1000 and 2500, and for Stanton numbers between 10 and 500.

Summary

There is still much research to be done in the field of direct contact heat exchange. But, with the effort of food engineers, approaches for the safe design and use of DSI heating for liquid food products may yet be developed.

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APPENDICES

APPENDIX A

PUMP CALIBRATION CURVE

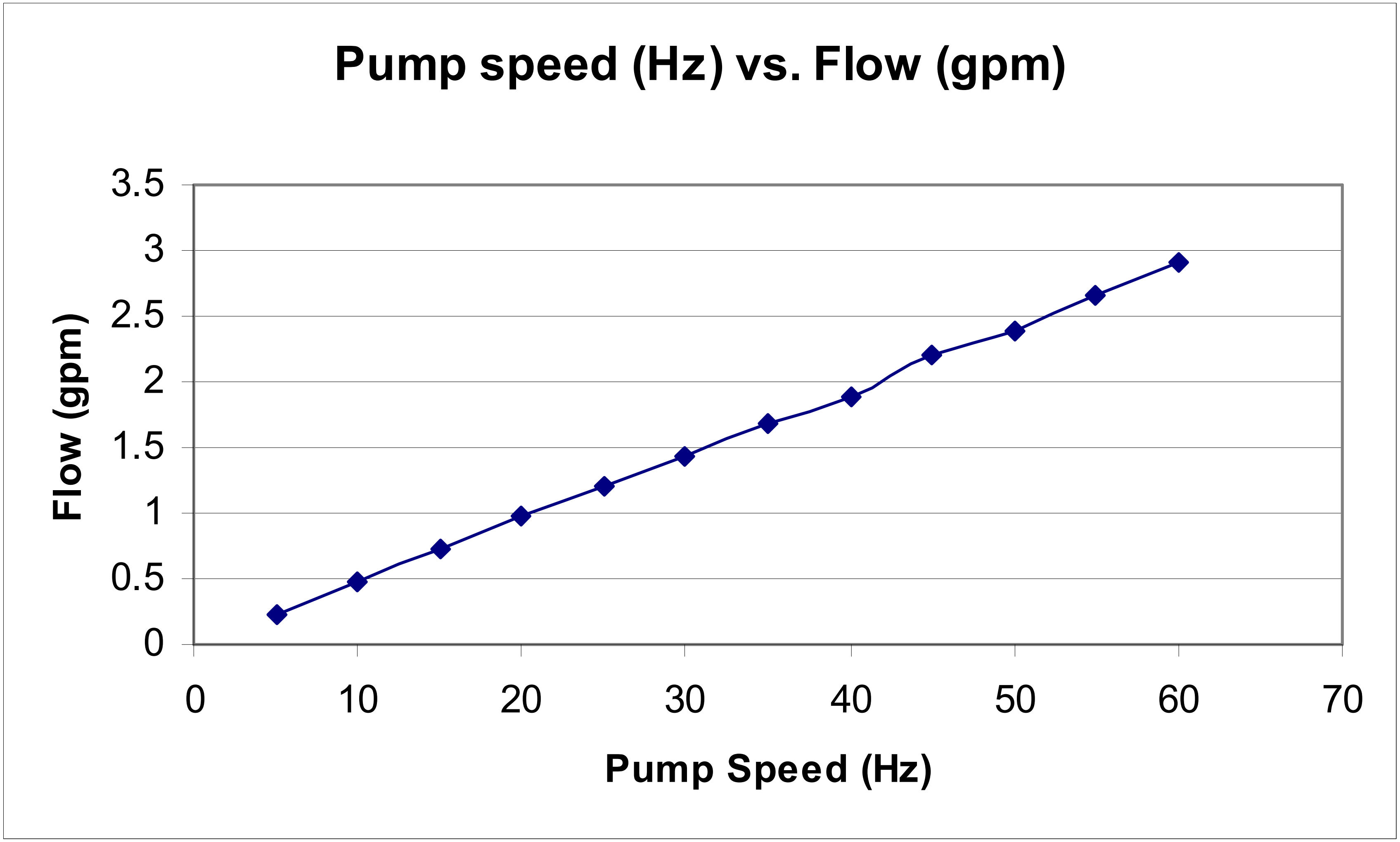


Figure A- 1: Pump calibration curve for Waukesha Cherry-Burrell, Delavan, WI, Model 15 positive displacement pump.

APPENDIX B

THERMAL DIFFUSIVITY CALCULATIONS

For food products the physical properties at various temperatures can be determined based on the amounts of protein, fat, carbohydrate, fiber, ash, water, and ice in the product using Equation B1 and the temperature functions in Table B-1.

$$k = \sum_{i=1}^{n} k_i X_i \qquad \text{Equation B1}$$

where n is the number of components, k_i is the thermal conductivity of the i^{th} component, and X_i is the mass fraction of the i^{th} component (Singh and Heldman, 2001). Equation B1 is equally applicable to density, specific heat, and thermal diffusivity.

Table B- 1: Coefficients to estimate food physical properties (Singh and Heldman, 2001).

Property	Component	Temperature Function
k	Protein	$k=1.7881x10^{-1} + 1.1958x10^{-3}T - 2.7178x10^{-6}T^2$
	Fat	$k=1.8071x10^{-1} – 2.7604x10^{-3}T - 1.7749x10^{-6}T^2$
	Carbohydrate	$k=2.0141x10^{-1} + 1.3874x10^{-3}T - 4.3312x10^{-6}T^2$
	Ash	$k=3.2962x10^{-1} + 1.4011x10^{-3}T - 2.9069x10^{-6}T^2$
	Water	$k=5.7109x10^{-1} + 1.7625x10^{-3}T - 6.7036x10^{-6}T^2$
ρ	Protein	$\rho=1.3299x10^{3} - 5.1840x10^{-1}T$
	Fat	$\rho=9.2559x10^{2} - 4.1757x10^{-1}T$
	Carbohydrate	$\rho=1.5991x10^{3} - 3.1046x10^{-1}T$
	Ash	$\rho=2.4238x10^{3} - 2.8063x10^{-1}T$
	Water	$\rho=9.9718x10^{2} + 3.1439x10^{-3}T - 3.7574x10^{-3}T^2$
c_p	Protein	$c_p=2.0082 + 1.2089x10^{-3}T – 1.3129x10^{-6}T^2$
	Fat	$\rho=1.9842 + 1.4733x10^{-3}T – 4.8008x10^{-6}T^2$
	Carbohydrate	$\rho=1.5488 + 1.9625x10^{-3}T – 5.9399x10^{-6}T^2$
	Ash	$\rho=1.0926 + 1.8896x10^{-3}T – 3.6817x10^{-6}T^2$
	Water	$\rho=4.1762 – 9.0864x10^{-5}T + 5.4731x10^{-6}T^2$

$$\alpha = \frac{k}{\rho c_p}$$ Equation B2 (Singh and Heldman, 2001)

where α is thermal diffusivity (m^2s^{-1}), k is thermal conductivity ($Wm^{-1}C^{-1}$), ρ is density (kgm^{-3}), and c_p is specific heat ($kJkg^{-1}K^{-1}$)

Table B- 2: Physical properties of the products tested.

Tester	Product	Test	Ti ºC	ρ kg/m^3	α m^2/s	cp kJ/(kgC)	k W/m/C
Ostermann	Beef Stock	1	23.19	1198.19	1.08E-07	2.8514	0.370
Ostermann	Beef Stock	2	24.20	1197.85	1.08E-07	2.8522	0.370
Ostermann	Beef Stock	3	19.69	1199.35	1.08E-07	2.8486	0.368
Ostermann	Beef Stock	4	12.41	1201.58	1.07E-07	2.8428	0.365
Ostermann	Beef Stock	5	20.43	1199.09	1.08E-07	2.8492	0.369
Ostermann	Beef Stock	6	17.62	1199.99	1.08E-07	2.8469	0.367
Ostermann	Beef Stock	7	14.21	1201.04	1.07E-07	2.8442	0.366
Ostermann	Beef Stock	8	17.87	1199.91	1.08E-07	2.8471	0.368
Ostermann	Beef Stock	9	23.12	1198.21	1.08E-07	2.8513	0.370
Ostermann	Beef Stock	10	23.62	1198.05	1.08E-07	2.8517	0.370
Ostermann	Beef Stock	11	11.95	1201.72	1.07E-07	2.8424	0.364
Ostermann	Beef Stock	12	12.50	1201.56	1.07E-07	2.8429	0.365
Ostermann	Beef Stock	13	11.75	1201.78	1.07E-07	2.8423	0.364
Ostermann	Beef Stock	14	13.83	1201.16	1.07E-07	2.8439	0.365
Ostermann	Beef Stock	15	15.76	1200.57	1.07E-07	2.8455	0.366
Ostermann	Beef Stock	16	23.25	1198.17	1.08E-07	2.8514	0.370
Ostermann	Beef Stock	17	28.15	1196.51	1.09E-07	2.8554	0.372
Ostermann	Beef Stock	18	21.89	1198.62	1.08E-07	2.8504	0.370
Ostermann	Beef Stock	19	22.39	1198.45	1.08E-07	2.8508	0.370
Ostermann	Beef Stock	20	25.97	1197.26	1.09E-07	2.8536	0.371
Ostermann	Beef Stock	21	33.72	1194.52	1.10E-07	2.8599	0.375
Ostermann	Beef Stock	22	33.46	1194.62	1.10E-07	2.8597	0.375
Ostermann	Corn Starch	1	36.55	1039.17	1.44E-07	3.9780	0.597
Ostermann	Corn Starch	2	45.47	1036.44	1.47E-07	3.9820	0.607
Ostermann	Corn Starch	4	41.30	1037.79	1.46E-07	3.9800	0.602
Ostermann	Corn Starch	5	45.28	1036.51	1.47E-07	3.9819	0.607
Ostermann	Corn Starch	6	43.47	1037.10	1.47E-07	3.9810	0.605
Ostermann	Corn Starch	7	35.40	1056.90	1.44E-07	3.9024	0.584

Table B- 2: Physical properties of products tested, continued

Tester	Product	Test	Ti ºC	ρ kg/m^3	α m^2/s	cp kJ/(kgC)	k W/m/C
Ostermann	Sugar Water	2	16.80	1302.38	1.10E-07	2.8462	0.407
Ostermann	Sugar Water	5	23.60	1299.61	1.12E-07	2.8578	0.416
Ostermann	Sugar Water	6	27.60	1295.03	1.14E-07	2.8771	0.424
Ostermann	Sugar Water	10	15.00	1297.98	1.09E-07	2.8653	0.407
Ostermann	Sugar Water	12	23.00	1292.60	1.13E-07	2.8883	0.420
Ostermann	Sugar Water	13	23.70	1292.43	1.13E-07	2.8889	0.421
Bowser	Sugar Water	1	34.17	1399.75	1.07E-07	2.4235	0.364
Bowser	Sugar Water	2	21.50	1390.19	1.04E-07	2.4650	0.357
Bowser	Sugar Water	3	43.06	1368.94	1.12E-07	2.5545	0.392
Bowser	Sugar Water	4	43.06	1368.94	1.12E-07	2.5545	0.392
Bowser	Sugar Water	5	43.06	1368.94	1.12E-07	2.5545	0.392
Bowser	Sugar Water	6	23.72	1366.15	1.07E-07	2.5695	0.375
Bowser	Sugar Water	7	23.72	1366.15	1.07E-07	2.5695	0.375
Bowser	Sugar Water	8	23.72	1366.15	1.07E-07	2.5695	0.375
Bowser	Sugar Water	9	41.56	1353.51	1.13E-07	2.6213	0.401
Bowser	Sugar Water	10	41.56	1353.51	1.13E-07	2.6213	0.401
Bowser	Sugar Water	11	24.89	1347.36	1.09E-07	2.6509	0.388
Bowser	Sugar Water	12	24.89	1347.36	1.09E-07	2.6509	0.388
Bowser	Sugar Water	13	24.89	1347.36	1.09E-07	2.6509	0.388
Bowser	Sugar Water	14	24.89	1347.36	1.09E-07	2.6509	0.388
Bowser	Sugar Water	15	24.89	1347.36	1.09E-07	2.6509	0.388
Bowser	Sugar Water	16	26.67	1334.97	1.10E-07	2.7044	0.398
Bowser	Sugar Water	17	43.89	1294.85	1.18E-07	2.8727	0.440
Ostermann	Water	1	17.00	996.15	1.44E-07	4.1762	0.599
Ostermann	Water	2	16.90	996.16	1.44E-07	4.1762	0.599
Ostermann	Water	3	17.10	996.14	1.44E-07	4.1762	0.599
Ostermann	Water	5	18.31	995.98	1.45E-07	4.1764	0.601
Ostermann	Water	6	18.38	995.97	1.45E-07	4.1764	0.601
Ostermann	Water	7	17.70	996.06	1.44E-07	4.1763	0.600
Ostermann	Water	8	17.50	996.08	1.44E-07	4.1763	0.600
Bowser	Water	1	20.83	995.62	1.45E-07	4.1767	0.605
Bowser	Water	2	13.72	996.52	1.43E-07	4.1760	0.594
Bowser	Water	3	18.61	995.94	1.45E-07	4.1764	0.602
Bowser	Water	4	18.67	995.93	1.45E-07	4.1764	0.602
Bowser	Water	5	18.72	995.92	1.45E-07	4.1764	0.602
Bowser	Water	6	21.17	995.56	1.46E-07	4.1767	0.605
Bowser	Water	7	21.94	995.44	1.46E-07	4.1768	0.607

APPENDIX C

COLLECTED DATA

Table C1: Collected Data

Tester	Product	Test	Flow rate gpm	Viscosity cP	Pressure psi	Ti ºC	Tf ºC	Tsat ºC
Ostermann	Beef Stock	1	1.20	1236.5	20	23.19	64.90	126.2
Ostermann	Beef Stock	2	1.20	1155.3	15	24.20	72.60	121.2
Ostermann	Beef Stock	3	1.44	1485.2	20	19.69	51.10	126.2
Ostermann	Beef Stock	4	1.30	2995.08	25	12.41	33.90	130.6
Ostermann	Beef Stock	5	1.54	2068.29	20	20.43	46.30	126.2
Ostermann	Beef Stock	6	1.69	1796.45	15	17.62	65.90	121.2
Ostermann	Beef Stock	7	1.93	2443.88	20	14.21	31.50	126.2
Ostermann	Beef Stock	8	1.20	2110.79	15	17.87	48.30	121.2
Ostermann	Beef Stock	9	1.44	1356.49	27	23.12	46.40	132.3
Ostermann	Beef Stock	10	1.44	1009.65	20	23.62	66.90	126.2
Ostermann	Beef Stock	11	2.17	3105.06	12	11.95	58.70	117.8
Ostermann	Beef Stock	12	1.20	3163.18	14	12.50	63.10	120.1
Ostermann	Beef Stock	13	1.44	3462.53	17	11.75	49.00	123.3
Ostermann	Beef Stock	14	2.41	2653.86	14	13.83	30.80	120.1
Ostermann	Beef Stock	15	1.69	2270.15	16	15.76	55.80	122.2
Ostermann	Beef Stock	16	1.20	1636.46	19	23.25	55.40	125.2
Ostermann	Beef Stock	17	1.44	1109.64	20	28.15	53.30	126.2
Ostermann	Beef Stock	18	1.93	1300.25	35	21.89	56.10	138.3
Ostermann	Beef Stock	19	1.69	1327.74	17	22.39	72.80	123.3
Ostermann	Beef Stock	20	0.96	1108.39	27	25.97	60.11	132.3
Ostermann	Beef Stock	21	1.44	555.32	20	33.72	59.70	126.2
Ostermann	Beef Stock	22	1.20	352.84	15	33.46	59.50	121.2
Ostermann	Corn Starch	1	2.17	312.22	20	36.55	59.00	126
Ostermann	Corn Starch	2	1.44	518.45	30	45.47	68.00	134.5
Ostermann	Corn Starch	4	1.20	668.43	25	41.30	59.80	130.4
Ostermann	Corn Starch	5	1.20	706.55	32	45.28	87.80	136
Ostermann	Corn Starch	6	0.96	775.92	20	43.47	77.70	126
Ostermann	Corn Starch	7	1.44	1554.49	17	35.40	48.80	123.1

Table C1: Collected Data, continued

Tester	Product	Test	Flow rate gpm	Viscosity cP	Pressure psi	Ti ºC	Tf ºC	Tsat ºC
Ostermann	Sugar	2	2.65	26.58	14.80	16.80	56.30	122.76
Ostermann	Sugar	5	1.69	17.55	17.60	23.60	72.30	125.64
Ostermann	Sugar	6	2.17	12.76	29.30	27.60	70.00	135.84
Ostermann	Sugar	10	1.69	24.20	19.40	15.00	62.50	127.34
Ostermann	Sugar	12	1.93	14.12	28.20	23.00	68.70	134.92
Ostermann	Sugar	13	1.93	13.59	22.90	23.70	71.30	130.49
Bowser	Sugar	1	1.44	141.20	10.50	34.17	77.22	120.39
Bowser	Sugar	2	2.17	173.90	29.50	21.50	73.22	138.28
Bowser	Sugar	3	1.44	31.40	33.00	43.06	103.90	140.39
Bowser	Sugar	4	2.17	31.40	22.00	43.06	79.44	131.52
Bowser	Sugar	5	2.17	31.40	10.50	43.06	75.00	119.54
Bowser	Sugar	6	2.89	71.30	13.00	23.72	52.22	122.22
Bowser	Sugar	7	0.96	71.30	18.00	23.72	77.22	127.50
Bowser	Sugar	8	0.48	71.30	17.00	23.72	106.70	126.50
Bowser	Sugar	9	2.89	22.60	15.90	41.56	63.89	125.15
Bowser	Sugar	10	1.20	22.60	23.00	41.56	92.22	131.94
Bowser	Sugar	11	0.57	40.30	11.80	24.89	80.56	120.34
Bowser	Sugar	12	0.82	40.30	17.80	24.89	91.11	126.80
Bowser	Sugar	13	1.20	40.30	16.00	24.89	82.78	124.97
Bowser	Sugar	14	1.44	40.30	16.00	24.89	76.67	124.97
Bowser	Sugar	15	1.93	40.30	16.00	24.89	69.44	124.97
Bowser	Sugar	16	2.51	27.70	13.20	26.67	68.33	121.66
Bowser	Sugar	17	2.51	7.00	19.00	43.89	80.00	127.00
Ostermann	Water	1	1.91	1.08	35.00	17.00	77.30	138.12
Ostermann	Water	2	3.25	1.08	21.40	16.90	61.70	127.28
Ostermann	Water	3	1.16	1.08	23.00	17.10	97.10	128.71
Ostermann	Water	5	1.03	1.04	29.00	18.31	73.50	133.68
Ostermann	Water	6	1.03	1.04	29.50	18.38	79.20	134.07
Ostermann	Water	7	0.48	1.06	20.20	17.70	96.80	126.17
Ostermann	Water	8	1.66	1.06	32.00	17.50	94.10	135.96
Bowser	Water	1	3.80	0.97	26.00	20.83	51.50	131.27
Bowser	Water	2	2.35	1.18	14.00	13.72	61.11	119.89
Bowser	Water	3	1.06	1.03	28.00	18.61	84.72	132.89
Bowser	Water	4	1.15	1.03	24.00	18.67	87.89	129.58
Bowser	Water	5	1.80	1.03	23.00	18.72	83.89	128.71
Bowser	Water	6	0.48	0.97	26.00	21.17	88.89	131.27
Bowser	Water	7	0.23	0.95	20.00	21.94	98.89	125.98

APPENDIX D

CALCULATION OF METHODOLOGICAL ERROR ASSOCIATED WITH THE FINAL TEMPERATURE

The error associated with selecting the T_f value used in calculations was based on the range of temperature values in the oscillations surrounding the selected final temperature. An example of this range is shown in Figure D1 for test 12 of beef stock. Table D1 shows the range of T_f values for tests using beef stock and corn starch, with the average range being 5 °C. This average was assumed to be the methodological error for T_f.

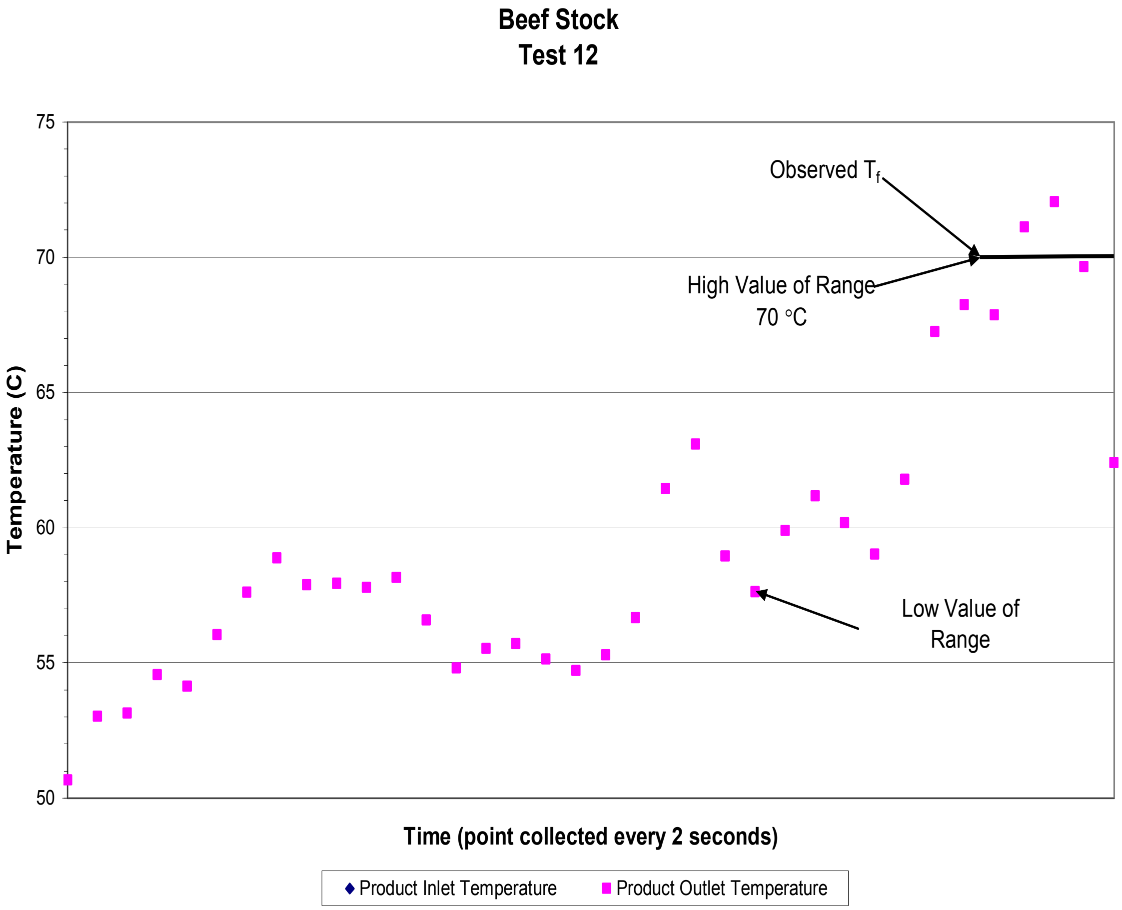


Figure D1: Example of methodological error in final temperature determination

Table D1: Variation in final temperature values

Product	Test	Tf ºC	Low	High	Difference Between Low and High
Beef Stock	1	64.90	63.10	67.60	4.5
Beef Stock	2	72.60	71.90	75.20	3.3
Beef Stock	3	51.10	50.00	52.40	2.4
Beef Stock	4	33.90	33.30	34.60	1.3
Beef Stock	5	46.30	44.90	48.00	3.1
Beef Stock	6	65.90	63.90	67.20	3.3
Beef Stock	7	31.50	27.90	38.06	10.2
Beef Stock	8	48.30	NA	NA	0.0
Beef Stock	9	46.40	43.80	46.40	2.6
Beef Stock	10	66.90	65.40	71.30	5.9
Beef Stock	11	58.70	56.10	65.40	9.3
Beef Stock	12	63.10	59.00	71.10	12.1
Beef Stock	13	49.00	NA	NA	0.0
Beef Stock	14	30.80	27.00	37.00	10.0
Beef Stock	15	55.80	NA	NA	0.0
Beef Stock	16	55.40	NA	NA	0.0
Beef Stock	17	53.30	50.30	60.70	10.4
Beef Stock	18	56.10	54.50	57.40	2.9
Beef Stock	19	72.80	NA	NA	0.0
Beef Stock	20	60.11	58.80	60.11	1.3
Beef Stock	21	59.70	58.20	60.70	2.5
Beef Stock	22	59.50	NA	NA	0.0
Corn Starch	1	59.00	49.00	64.00	15.0
Corn Starch	2	68.00	66.40	73.10	6.7
Corn Starch	4	59.80	58.30	66.90	8.6
Corn Starch	5	87.80	84.30	94.40	10.1
Corn Starch	6	77.70	73.10	81.40	8.3
Corn Starch	7	48.80	45.70	54.70	9.0

APPENDIX E

TABULAR RESULTS OF THE CALCULATION OF DIMENTIONLESS PARAMETERS

Table E1: Calculated Dimensionless Parameters

Tester	Product	Test	R_T	Pe	Pr	Re	Nu	St	Ja
Ostermann	Beef Stock	1	2.47	21594	9529.07	2.27	7459	1.77	73.08
Ostermann	Beef Stock	2	2.00	21567	8905.80	2.43	8729	2.38	72.46
Ostermann	Beef Stock	3	3.39	26034	11496.58	2.27	6587	1.30	75.19
Ostermann	Beef Stock	4	5.50	23751	23327.16	1.02	3874	0.17	79.58
Ostermann	Beef Stock	5	4.09	27815	15970.11	1.74	5820	0.63	74.74
Ostermann	Beef Stock	6	2.15	30641	13935.46	2.20	11718	1.85	76.44
Ostermann	Beef Stock	7	6.48	35165	18991.48	1.85	4679	0.46	78.49
Ostermann	Beef Stock	8	3.40	21750	16330.52	1.33	5240	0.43	76.29
Ostermann	Beef Stock	9	4.69	25916	10453.41	2.48	4993	1.18	73.12
Ostermann	Beef Stock	10	2.37	25899	7781.67	3.33	9321	3.99	72.81
Ostermann	Beef Stock	11	2.26	39674	24246.77	1.64	14057	0.95	79.86
Ostermann	Beef Stock	12	2.13	21920	24637.27	0.89	8426	0.30	79.53
Ostermann	Beef Stock	13	2.99	26334	27037.22	0.97	7421	0.27	79.98
Ostermann	Beef Stock	14	6.26	43936	20677.57	2.13	5733	0.59	78.72
Ostermann	Beef Stock	15	2.66	30723	17649.49	1.74	9603	0.95	77.56
Ostermann	Beef Stock	16	3.17	21593	12611.36	1.71	5752	0.78	73.04
Ostermann	Beef Stock	17	3.90	25755	8517.38	3.03	5598	1.99	70.07
Ostermann	Beef Stock	18	3.40	34790	10016.84	3.47	9735	3.37	73.86
Ostermann	Beef Stock	19	2.00	30444	10230.06	2.97	12613	3.67	73.56
Ostermann	Beef Stock	20	3.11	17215	8525.34	2.02	4986	1.18	71.39
Ostermann	Beef Stock	21	3.56	25592	4235.09	6.04	6026	8.59	66.70
Ostermann	Beef Stock	22	3.37	21333	2690.71	7.92	5021	14.78	66.86
Ostermann	Corn Starch	1	3.98	29317	2080.42	14.08	6121	41.44	78.64
Ostermann	Corn Starch	2	3.95	19081	3401.10	5.61	4365	7.20	71.99
Ostermann	Corn Starch	4	4.82	16042	4419.19	3.63	2892	2.38	75.10
Ostermann	Corn Starch	5	2.13	15907	4634.94	3.43	6852	5.07	72.14
Ostermann	Corn Starch	6	2.41	12774	5105.68	2.50	4350	2.13	73.48
Ostermann	Corn Starch	7	6.54	19442	10387.40	1.91	2447	0.45	79.30

Table E1: Calculated Dimensionless Numbers, continued

Tester	Product	Test	R_T	Pe	Pr	Re	Nu	St	Ja
Ostermann	Sugar Water	2	2.68	47115	185.88	253.18	14614	19905	83.48
Ostermann	Sugar Water	5	2.10	29388	120.56	244.02	11900	24085	79.17
Ostermann	Sugar Water	6	2.55	37191	86.58	429.43	13544	67173	76.78
Ostermann	Sugar Water	10	2.36	30110	170.37	176.74	11088	11502	84.94
Ostermann	Sugar Water	12	2.45	33436	97.10	344.50	12634	44824	79.98
Ostermann	Sugar Water	13	2.24	33366	93.25	357.89	13206	50680	79.52
Bowser	Sugar Water	1	2.00	26141	940.10	27.83	10257	304	65.96
Bowser	Sugar Water	2	2.26	40636	1200.74	33.82	17148	483	74.32
Bowser	Sugar Water	3	1.60	25047	204.62	122.41	15097	9032	62.49
Bowser	Sugar Water	4	2.43	37745	204.62	184.47	13604	12264	62.49
Bowser	Sugar Water	5	2.39	37745	204.62	184.47	11944	10767	62.49
Bowser	Sugar Water	6	3.46	52816	488.55	107.97	12499	2762	74.75
Bowser	Sugar Water	7	1.94	17544	488.55	35.87	7794	572	74.75
Bowser	Sugar Water	8	1.24	8772	488.55	17.93	6044	222	74.75
Bowser	Sugar Water	9	3.74	49913	147.73	337.48	10868	24827	64.35
Bowser	Sugar Water	10	1.78	20725	147.73	140.13	10238	9711	64.35
Bowser	Sugar Water	11	1.71	10238	275.34	37.16	4782	645	75.32
Bowser	Sugar Water	12	1.54	14729	275.34	53.46	8183	1589	75.32
Bowser	Sugar Water	13	1.73	21554	275.34	78.23	10468	2974	75.32
Bowser	Sugar Water	14	1.93	25865	275.34	93.87	11236	3831	75.32
Bowser	Sugar Water	15	2.25	34667	275.34	125.82	12957	5921	75.32
Bowser	Sugar Water	16	2.28	44446	188.22	235.87	15763	19753	75.00
Bowser	Sugar Water	17	2.30	41355	45.70	905.31	14924	295626	65.93

Table E1: Calculated Dimensionless Numbers, continued

Tester	Product	Test	R_T	Pe	Pr	Re	Nu	St	Ja
Ostermann	Water	1	2.01	25799	7.53	3426.67	12251	5575180	93.54
Ostermann	Water	2	2.46	44005	7.53	5844.80	15512	12041250	93.61
Ostermann	Water	3	1.40	15707	7.53	2086.15	9903	2743604	93.46
Ostermann	Water	5	2.09	13794	7.23	1915.43	6078	1610982	92.56
Ostermann	Water	6	1.90	13794	7.23	1915.41	6702	1776274	92.51
Ostermann	Water	7	1.37	6555	7.38	887.02	4099	492770	93.02
Ostermann	Water	8	1.55	22500	7.38	3044.63	13603	5613169	93.17
Bowser	Water	1	3.60	51099	6.70	7605.12	12680	14400782	90.68
Bowser	Water	2	2.24	32032	8.30	3868.36	11673	5443280	95.98
Bowser	Water	3	1.73	14238	7.15	1996.28	7521	2101146	92.34
Bowser	Water	4	1.60	15464	7.15	2168.15	8557	2596328	92.30
Bowser	Water	5	1.69	24205	7.15	3393.60	12614	5990632	92.25
Bowser	Water	6	1.63	6379	6.70	955.88	3529	503758	90.43
Bowser	Water	7	1.35	3017	6.54	461.50	1902	134267	89.85

APPENDIX F

RESULTS OF LINEAR REGRESSION FOR GROUPED AND AVERAGED DATA VALUES

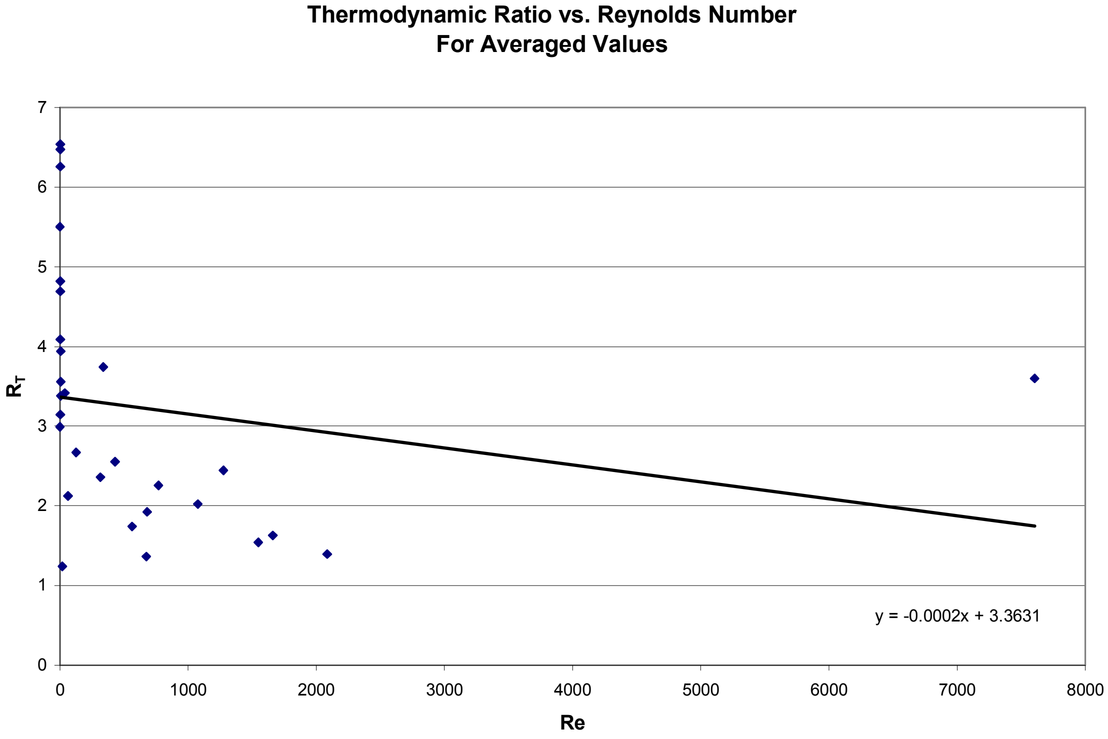


Figure F1: Linear regression of the relationship between averaged thermodynamic ratio and averaged Reynolds number.

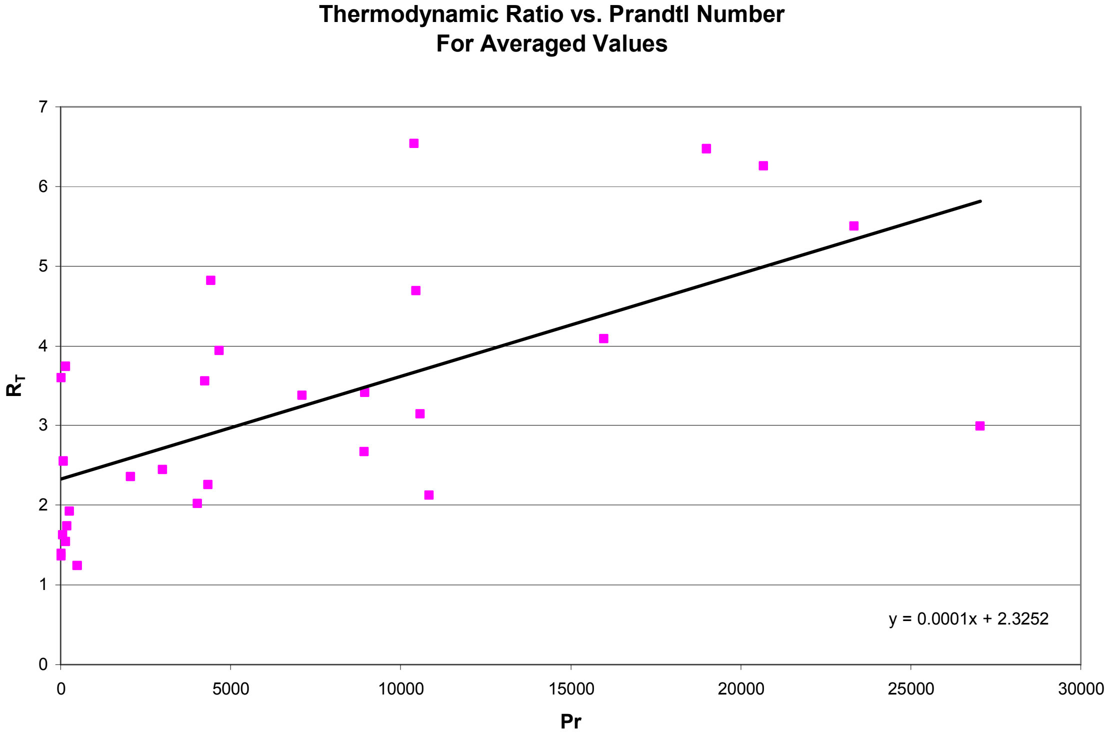


Figure F2: Linear regression of the relationship between averaged thermodynamic ratio and averaged Prandtl number.

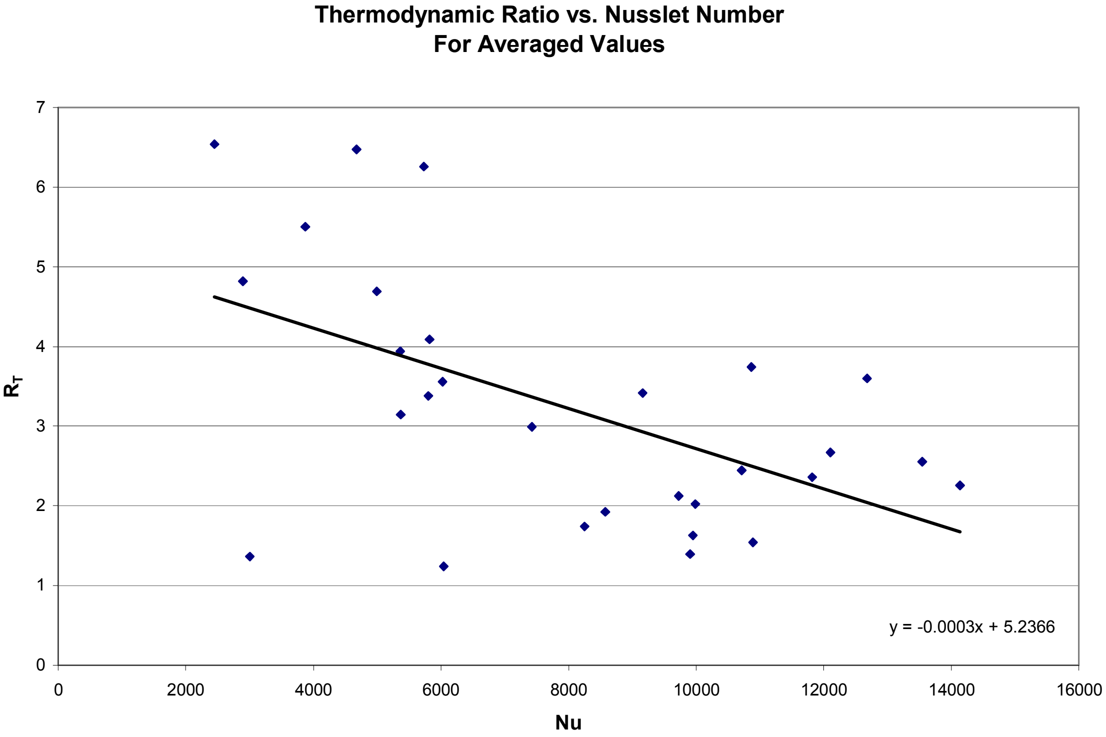


Figure F3: Linear regression of the relationship between averaged thermodynamic ratio and averaged Nusselt number.

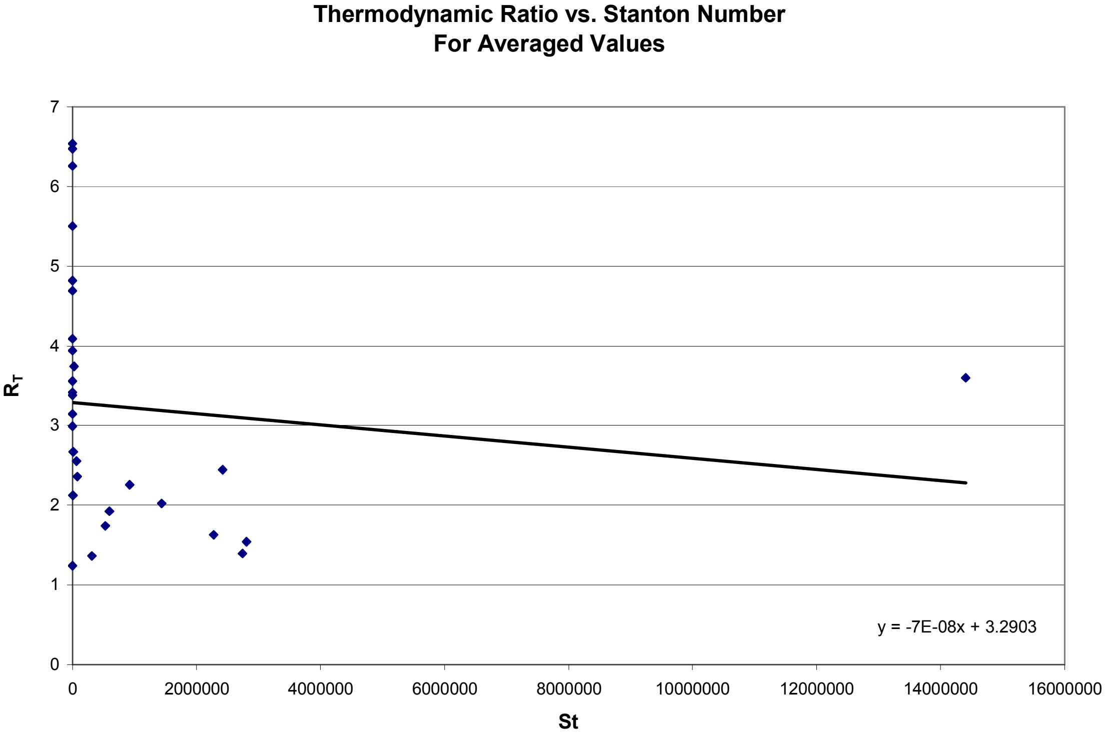


Figure F4: Linear regression of the relationship between averaged thermodynamic ratio and averaged Stanton number

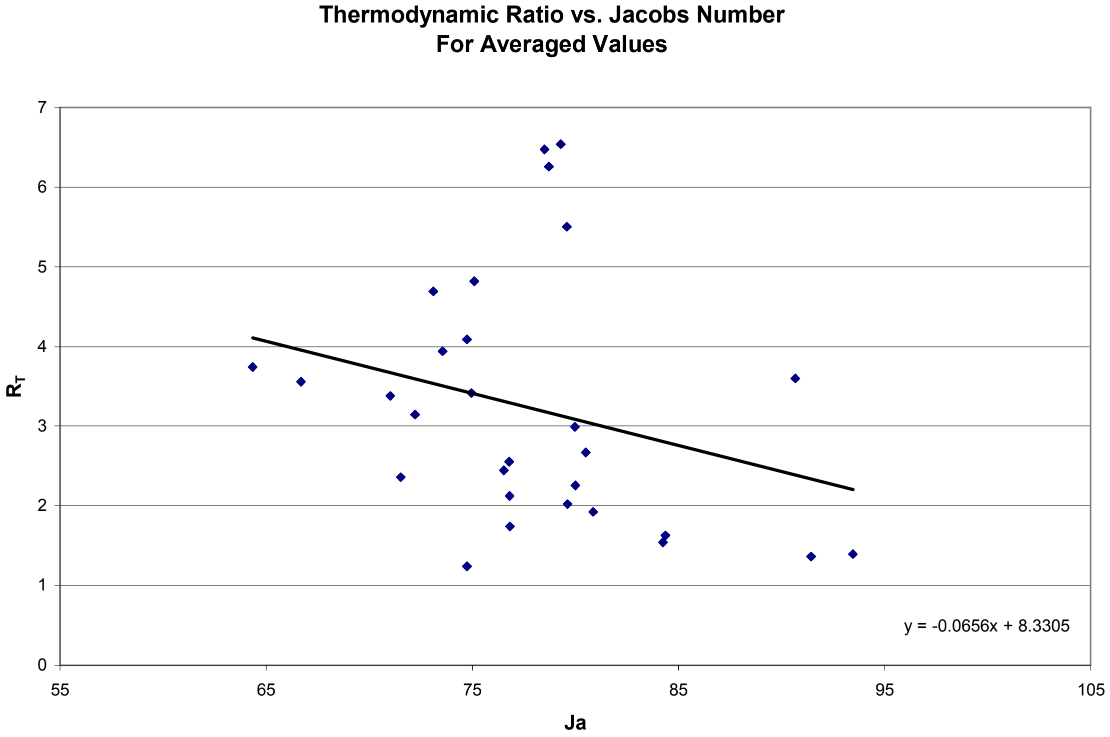


Figure F5: Linear regression of the relationship between averaged thermodynamic ratio and averaged Jacobs number

APPENDIX G

RESULTS OF REGRESSION ANALYSIS USING LOGRITHMIC, EXPONENTIAL, AND POWER RELATIONSHIPS

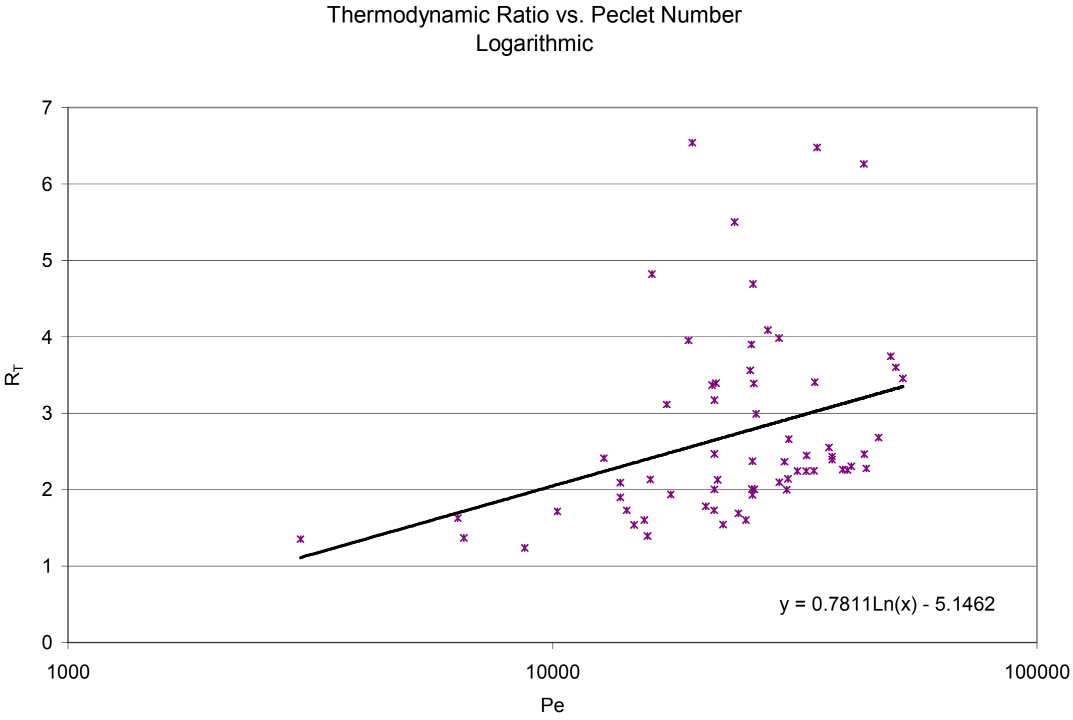


Figure G 1

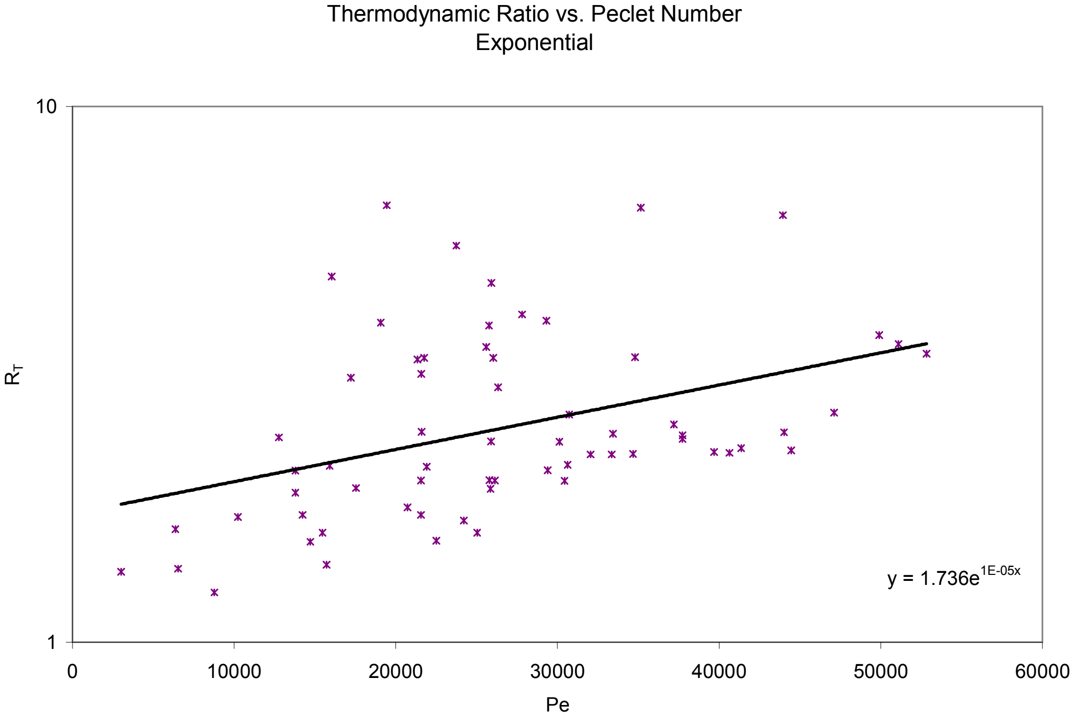


Figure G 1

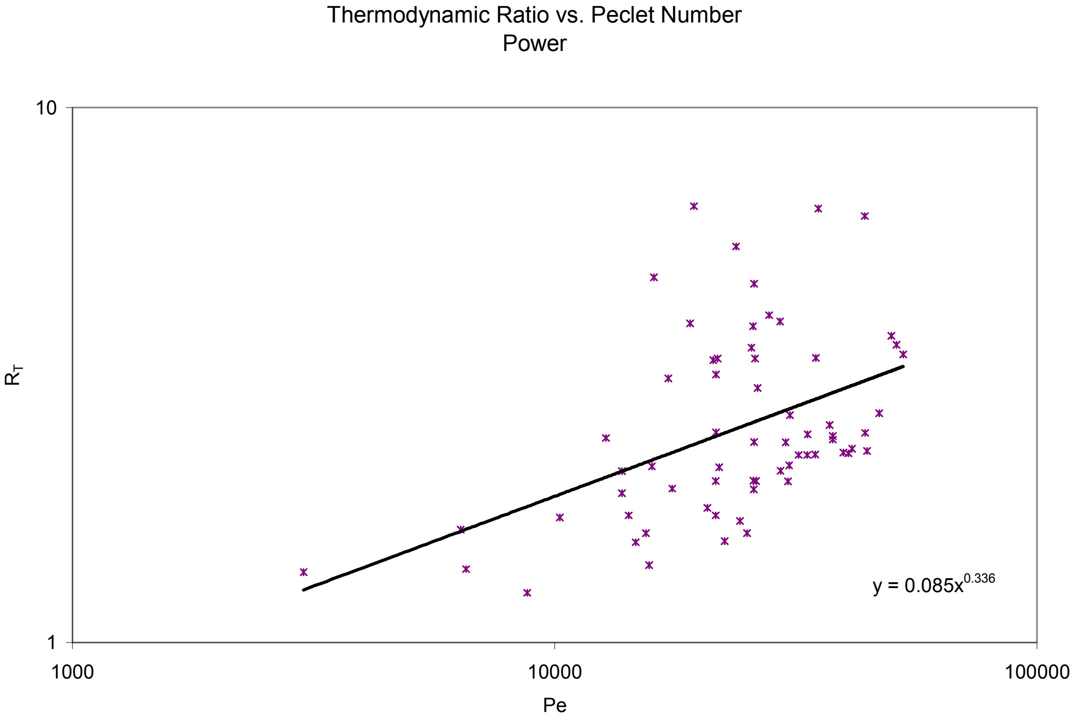


Figure G 2

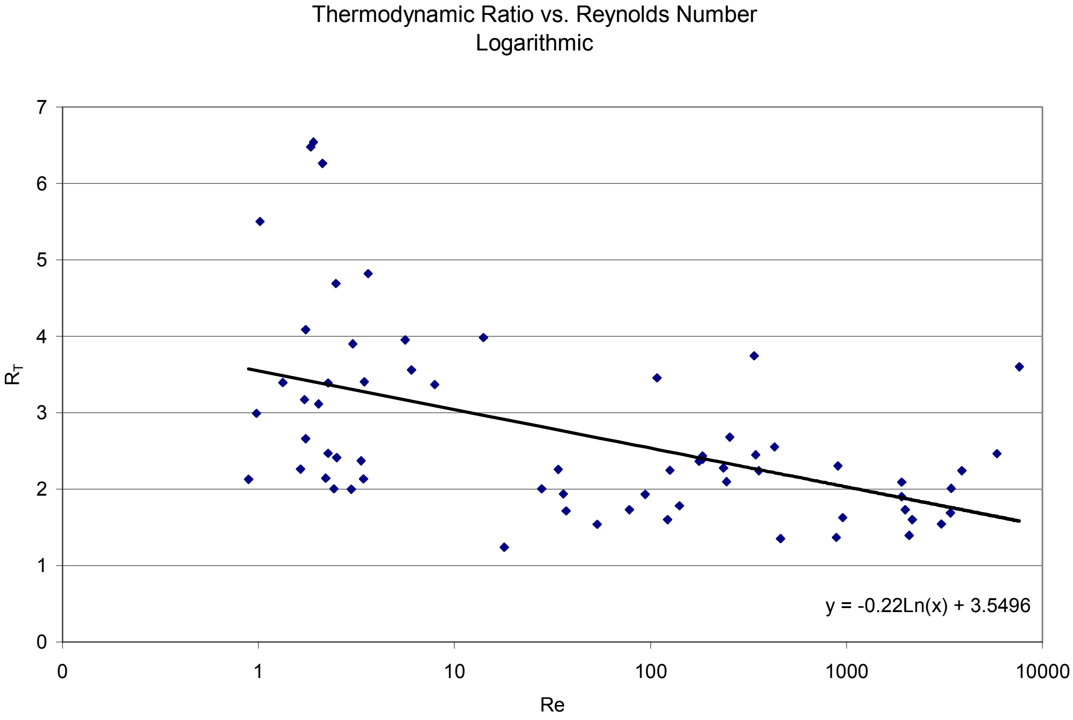
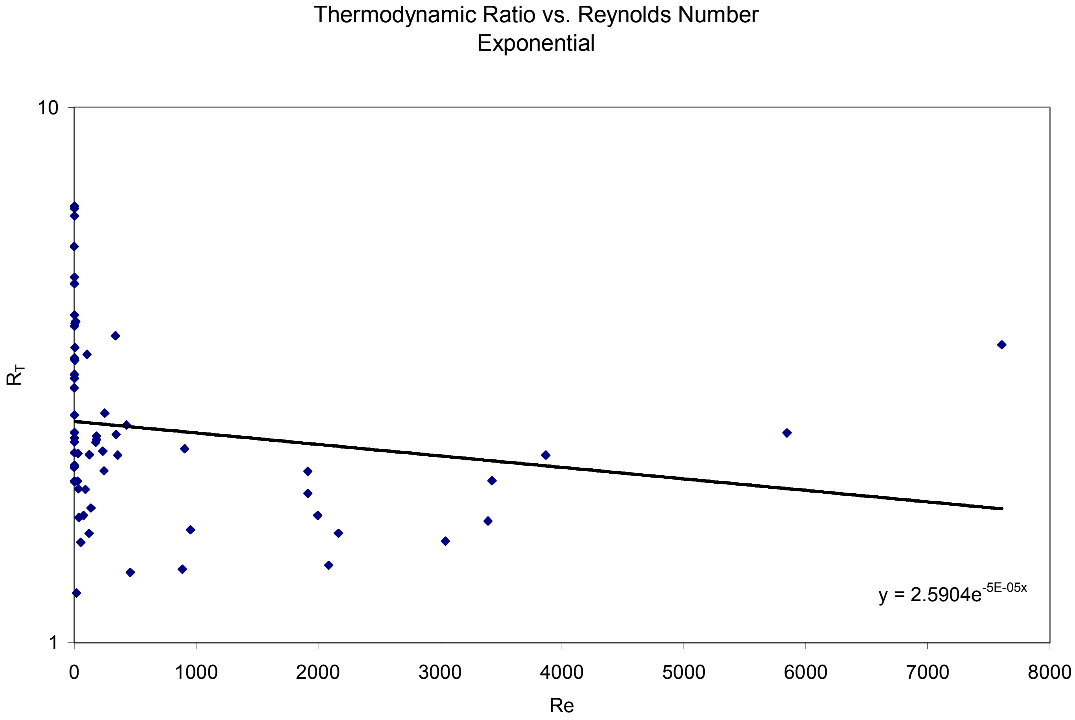


Figure G 3



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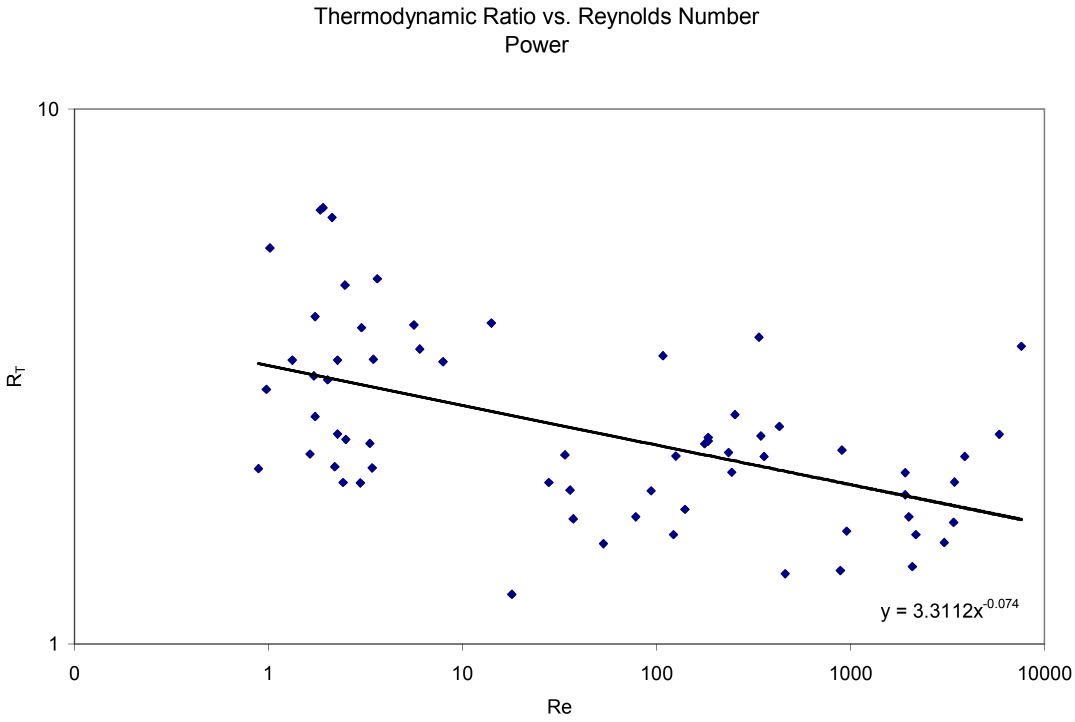

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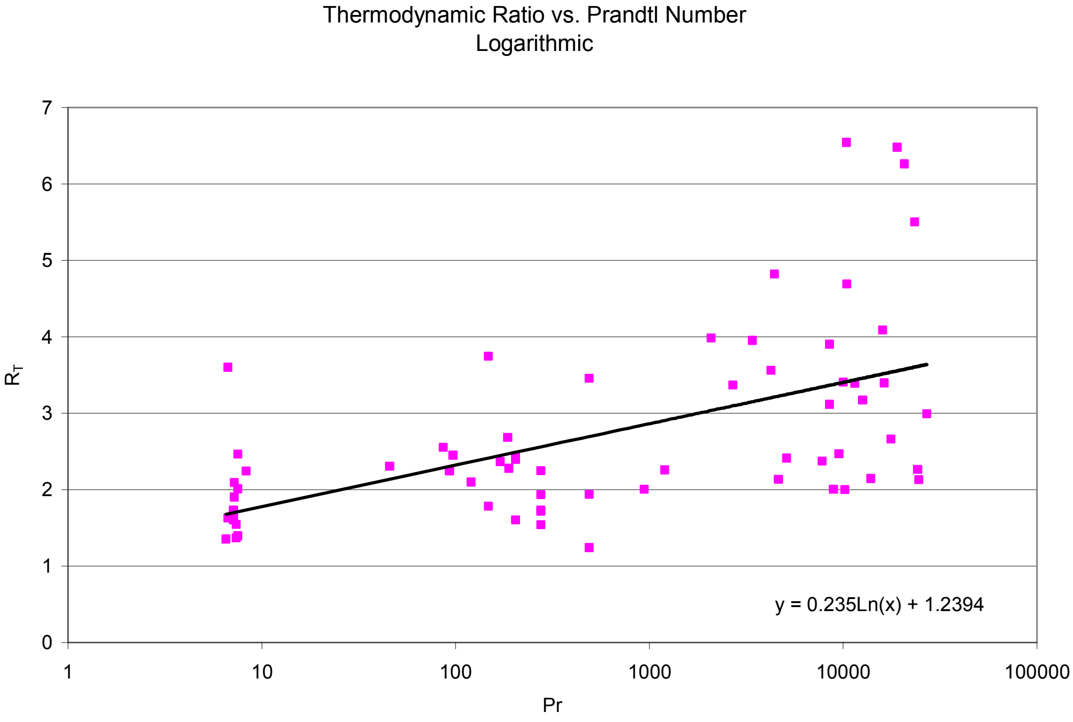

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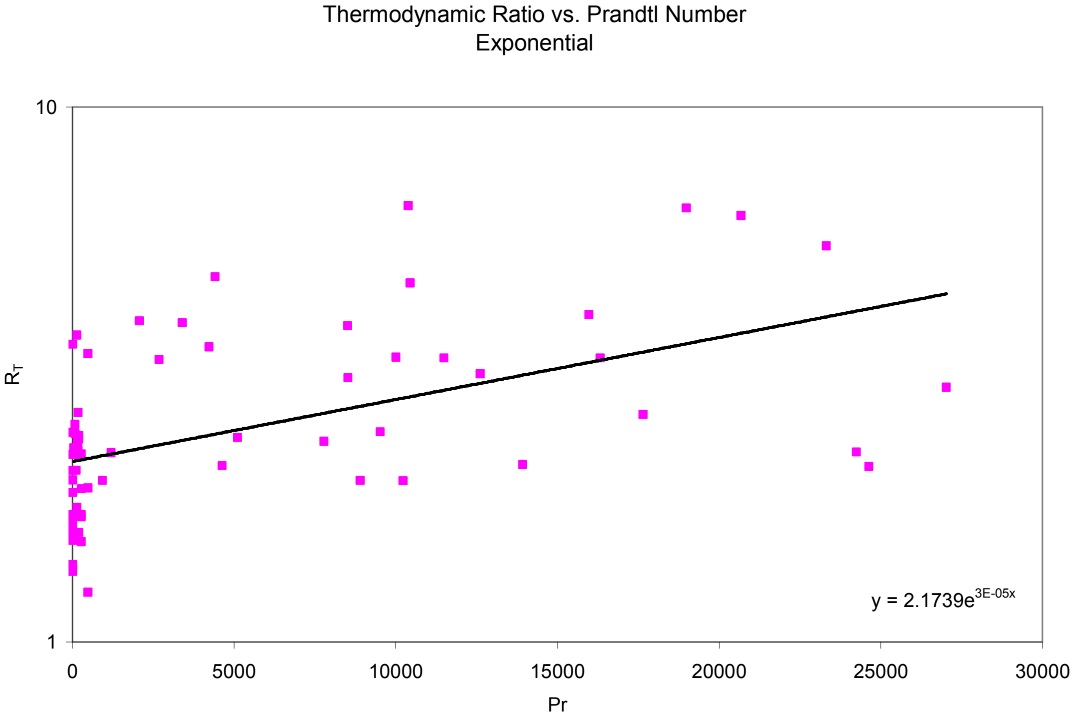

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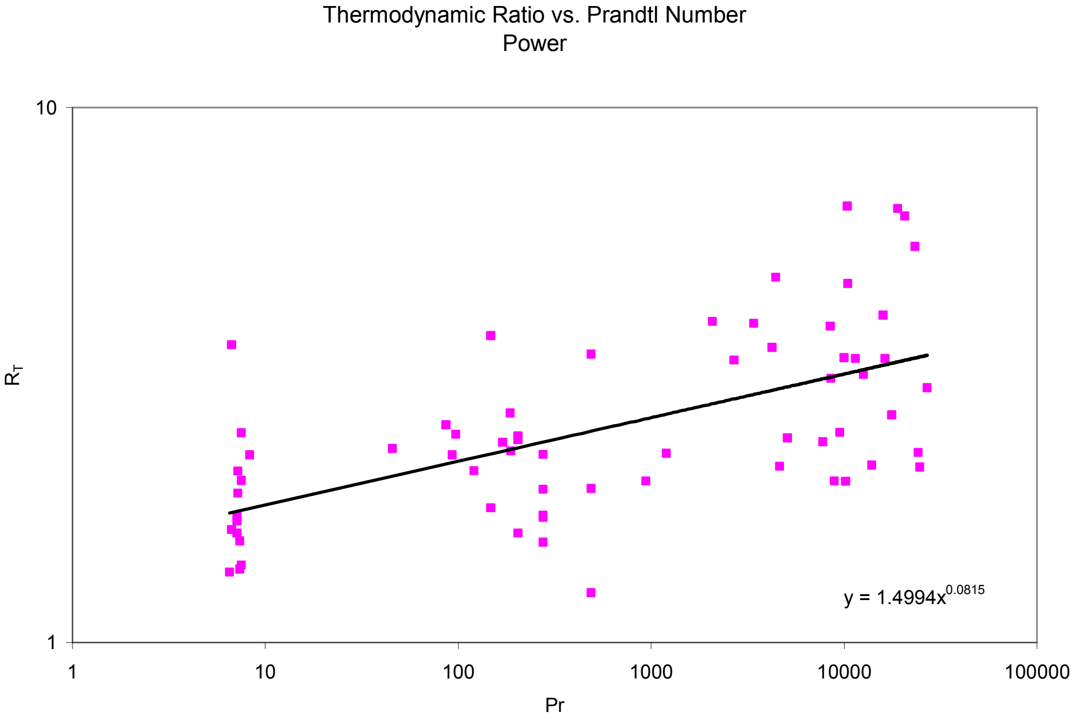
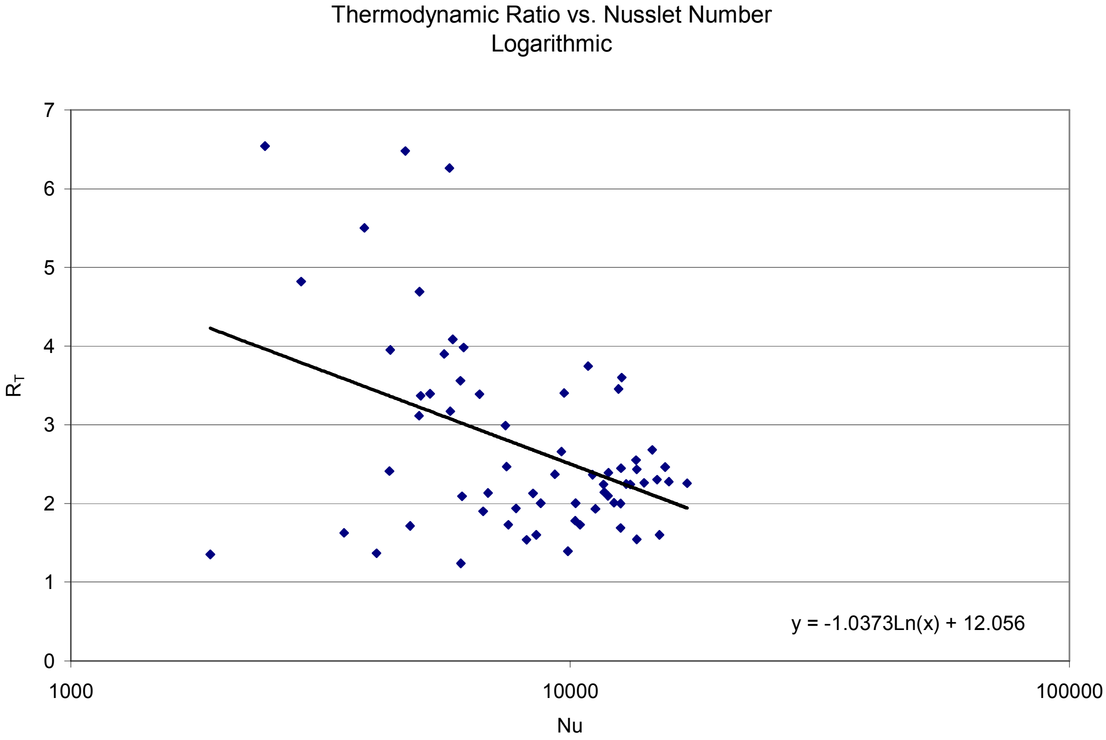


Figure G 8



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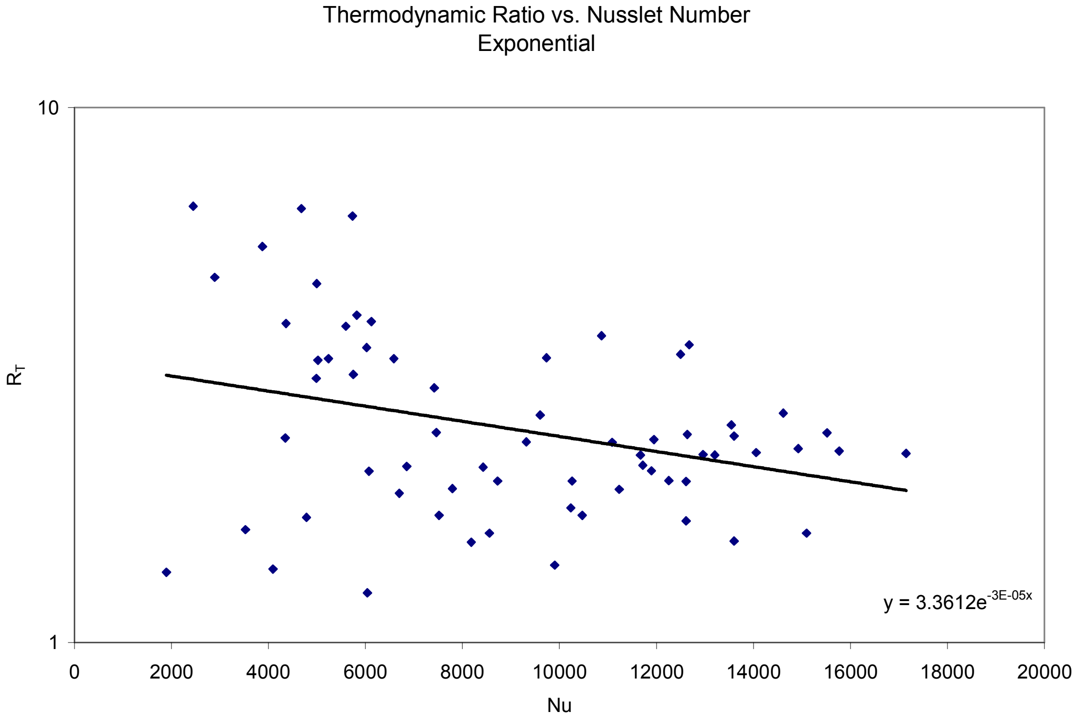

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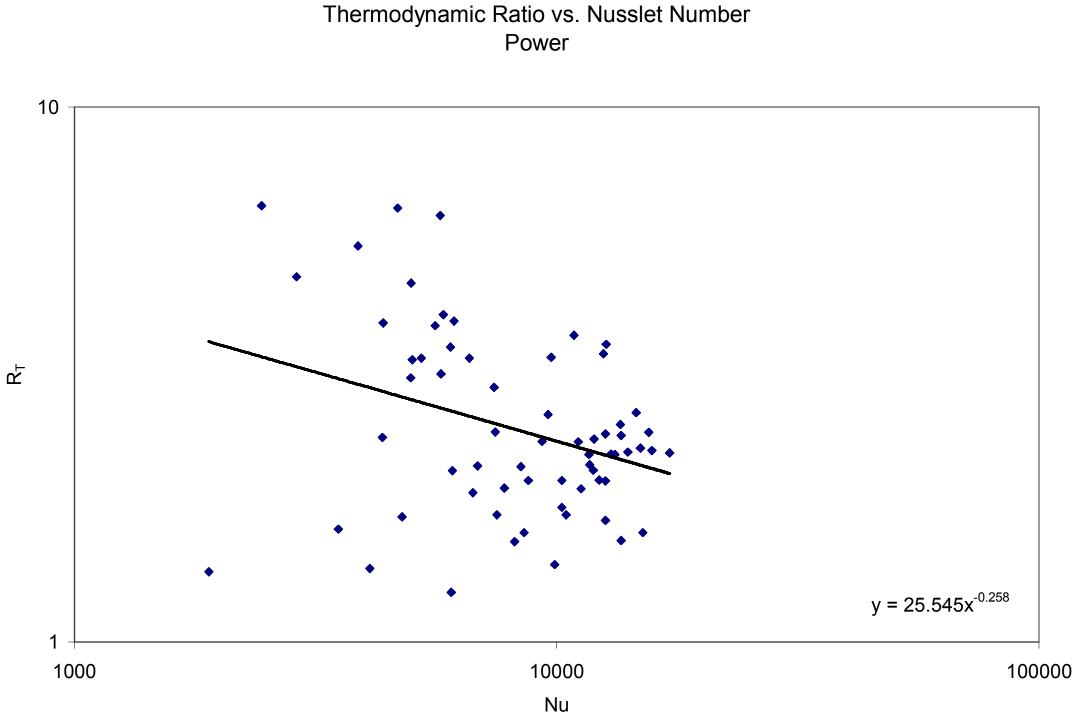

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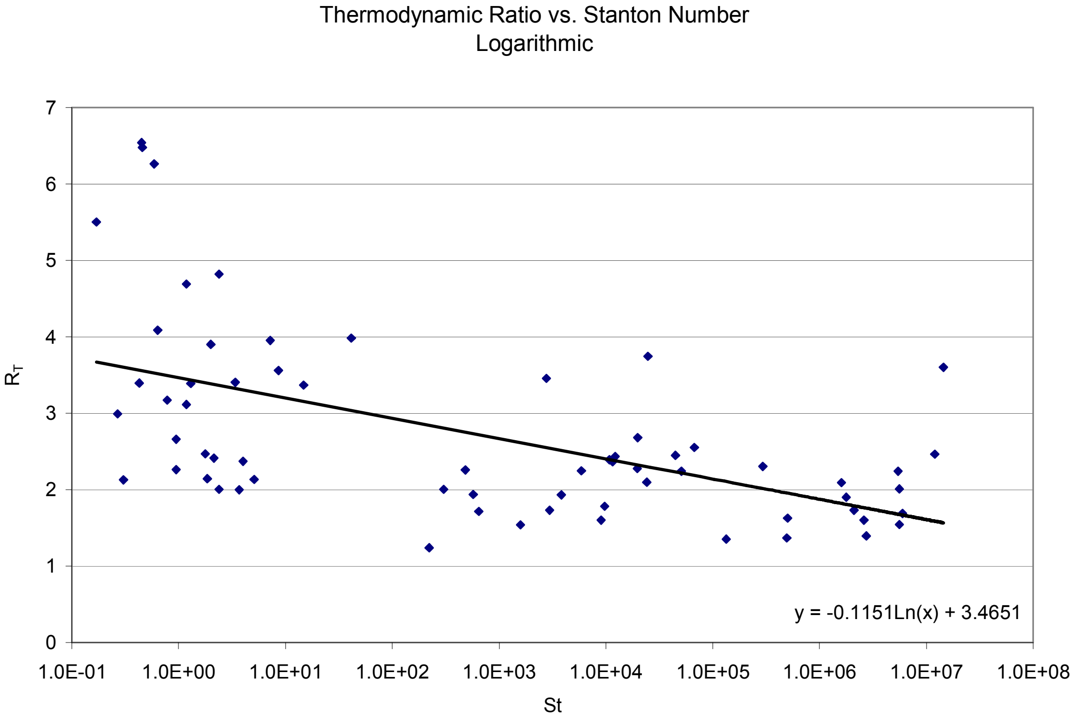

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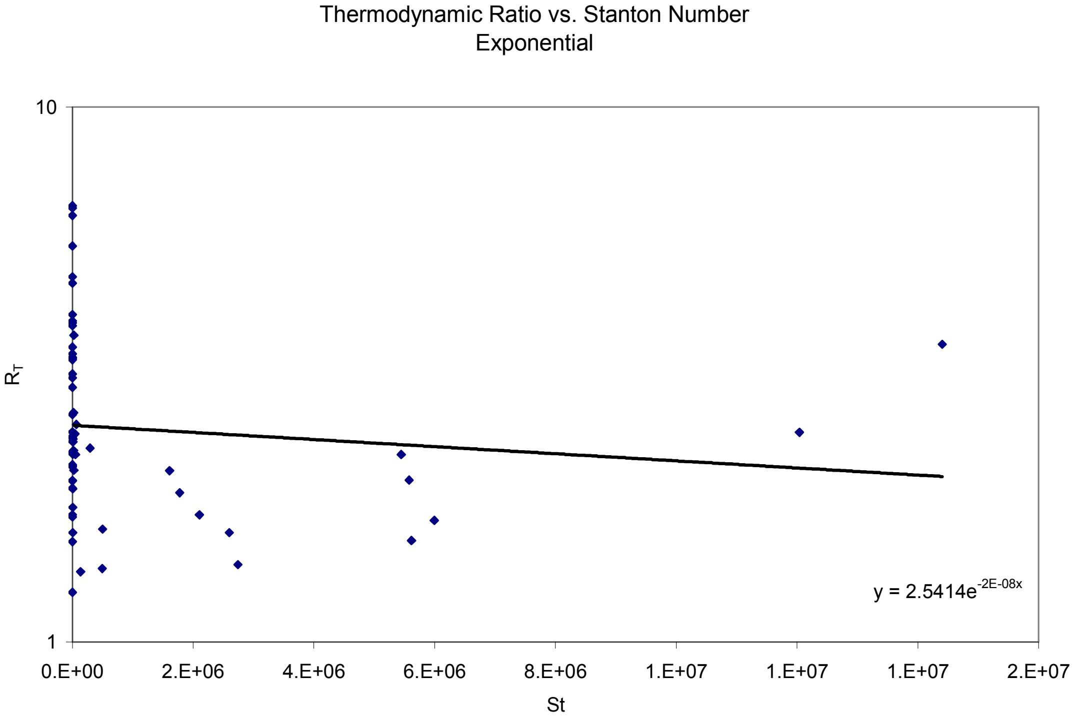

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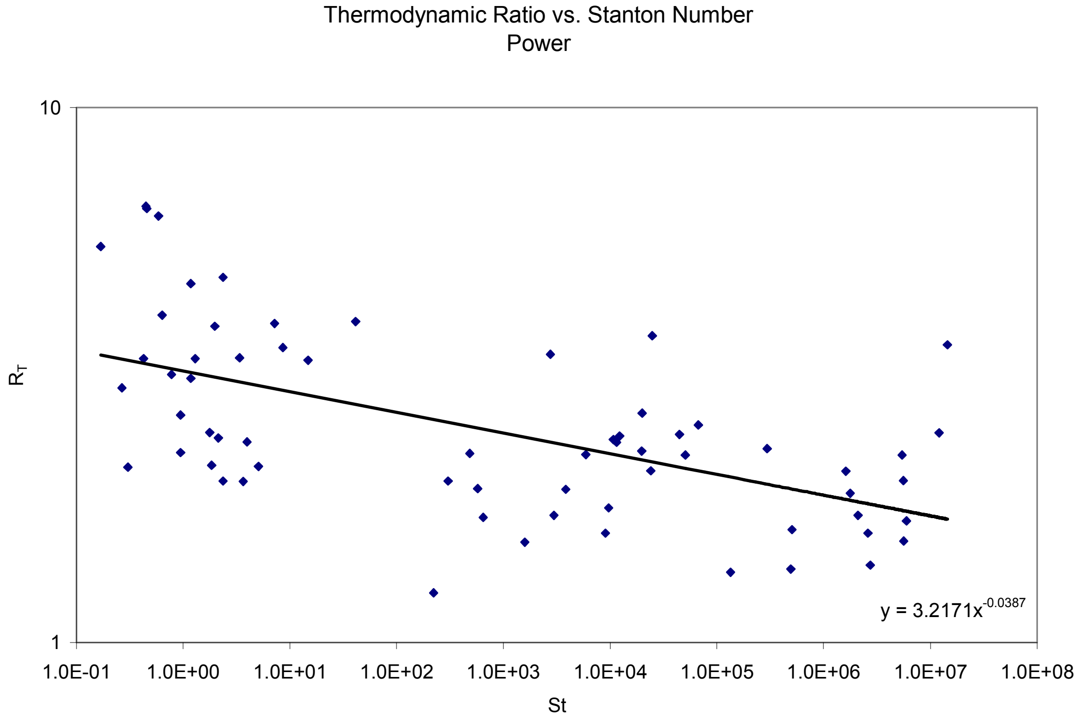

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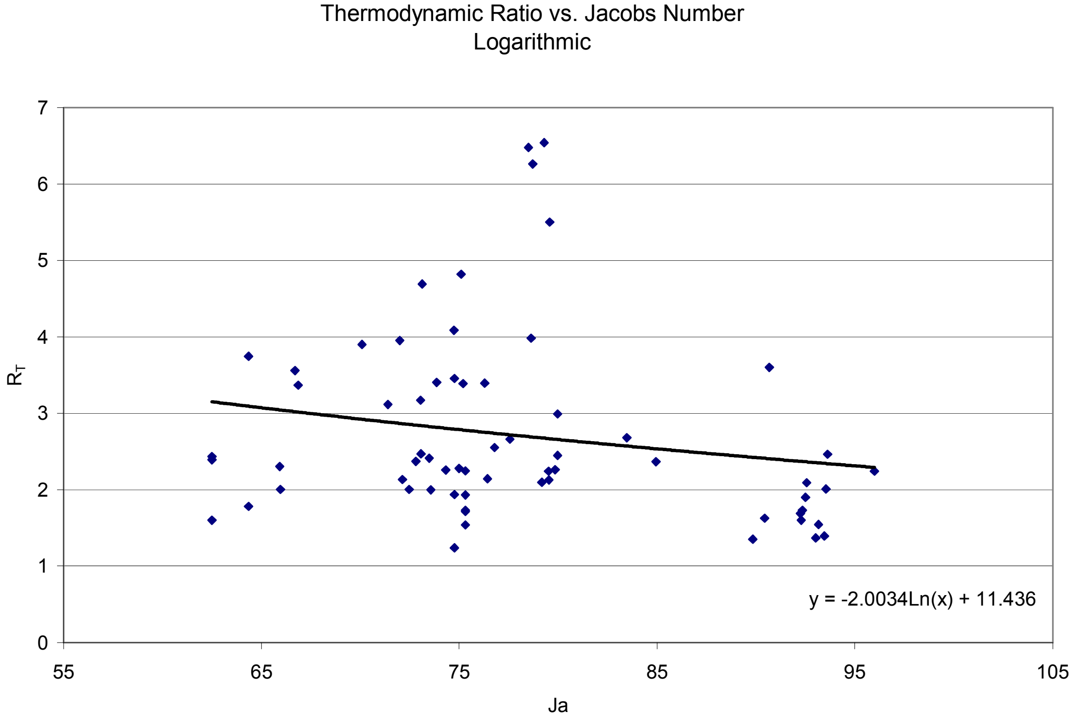

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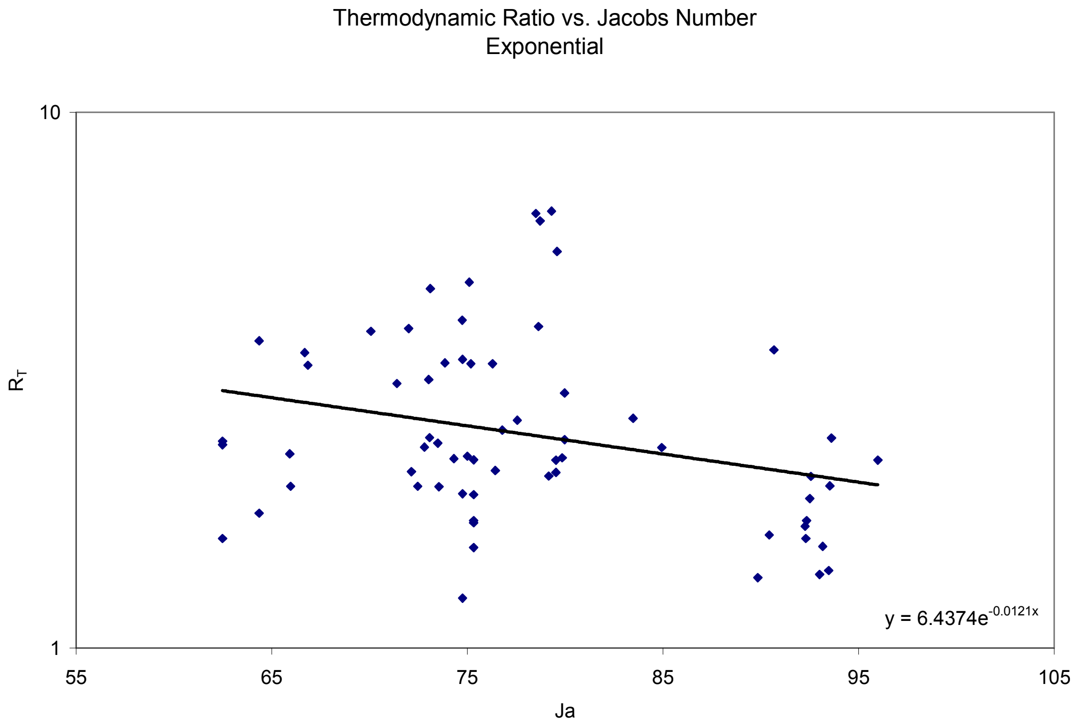

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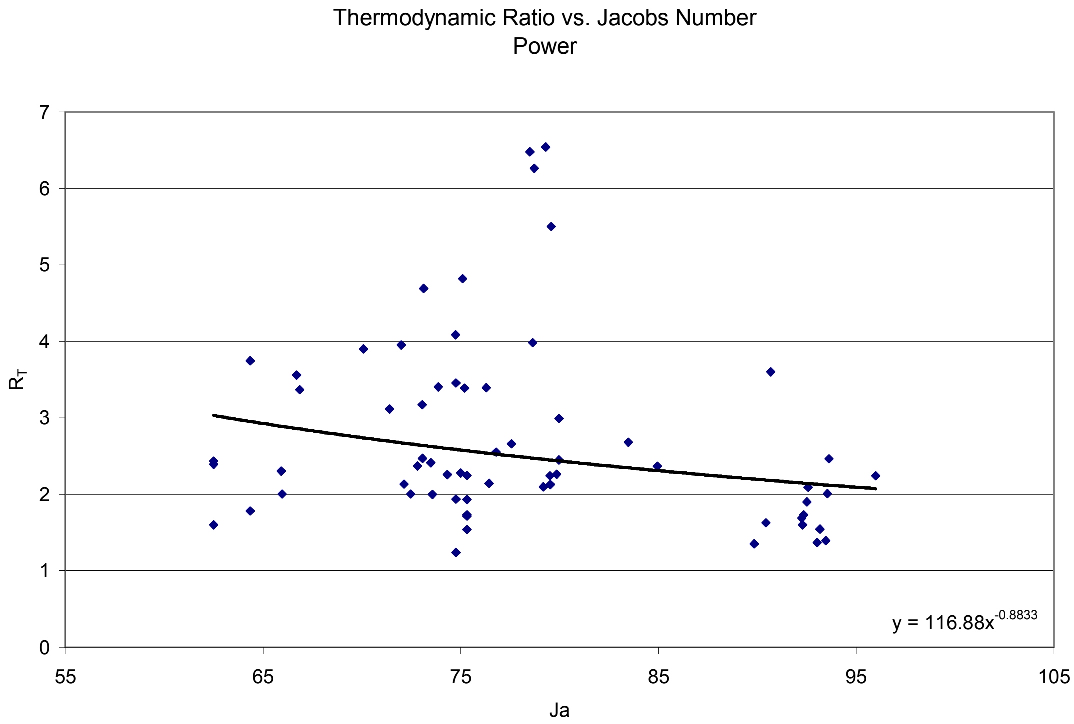

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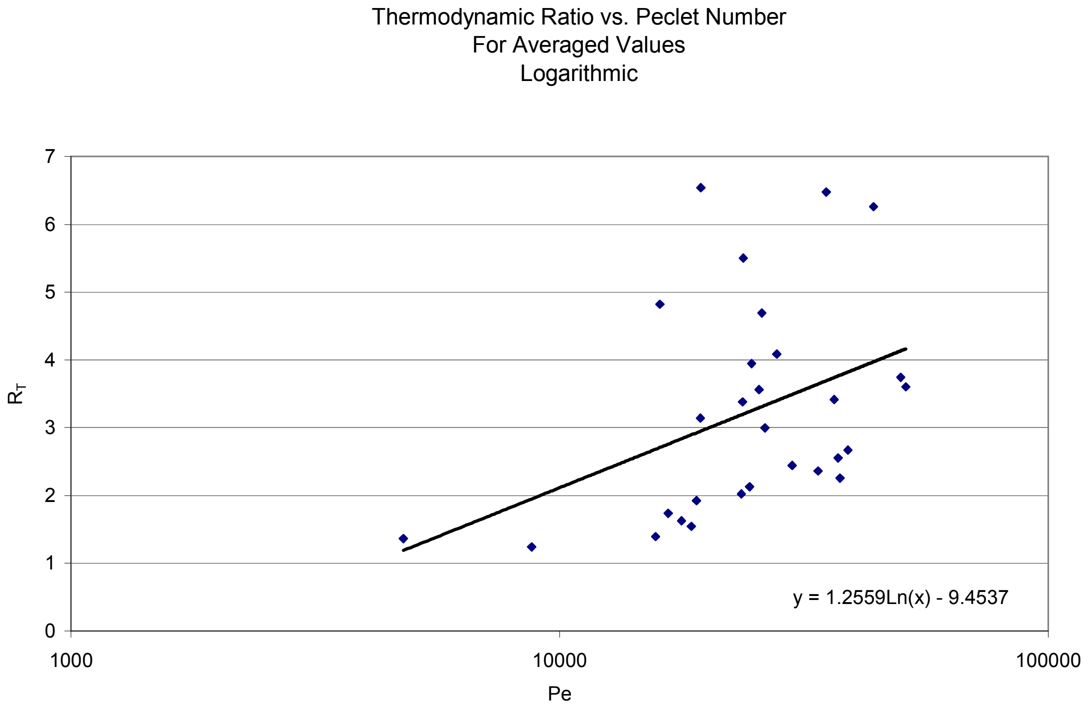

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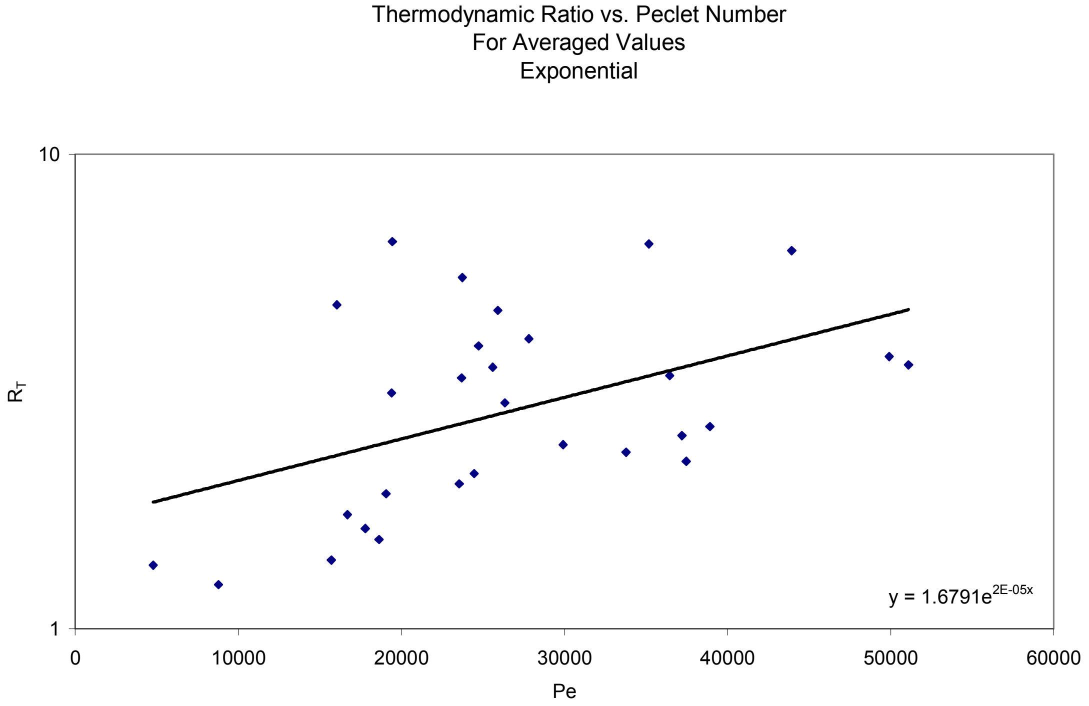

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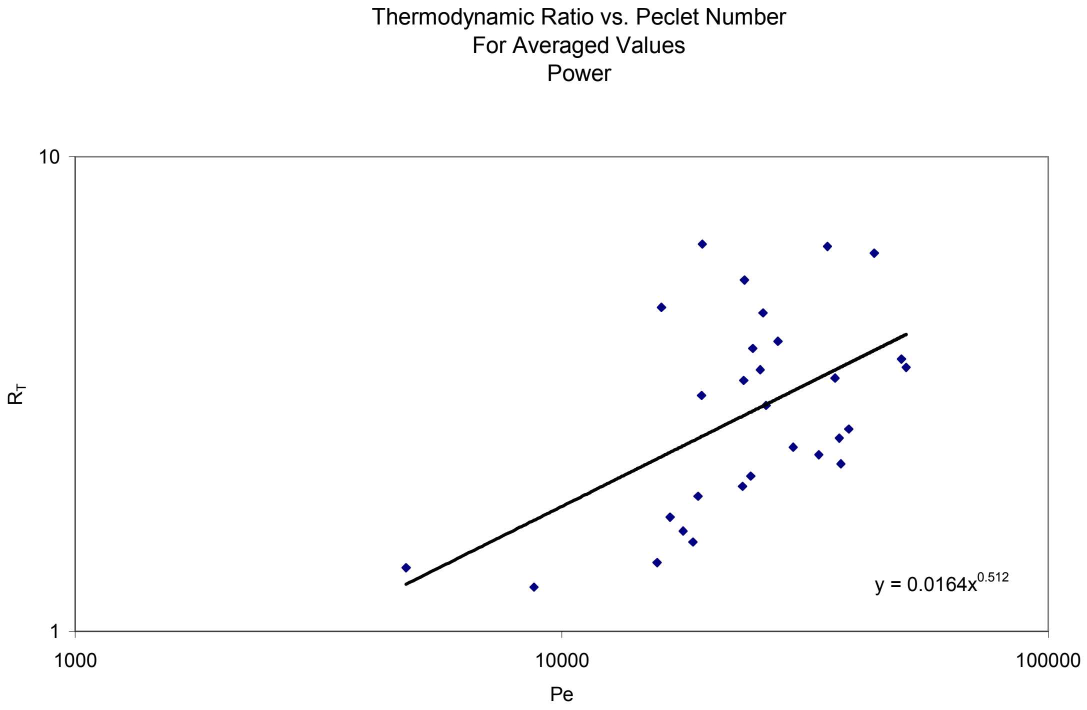

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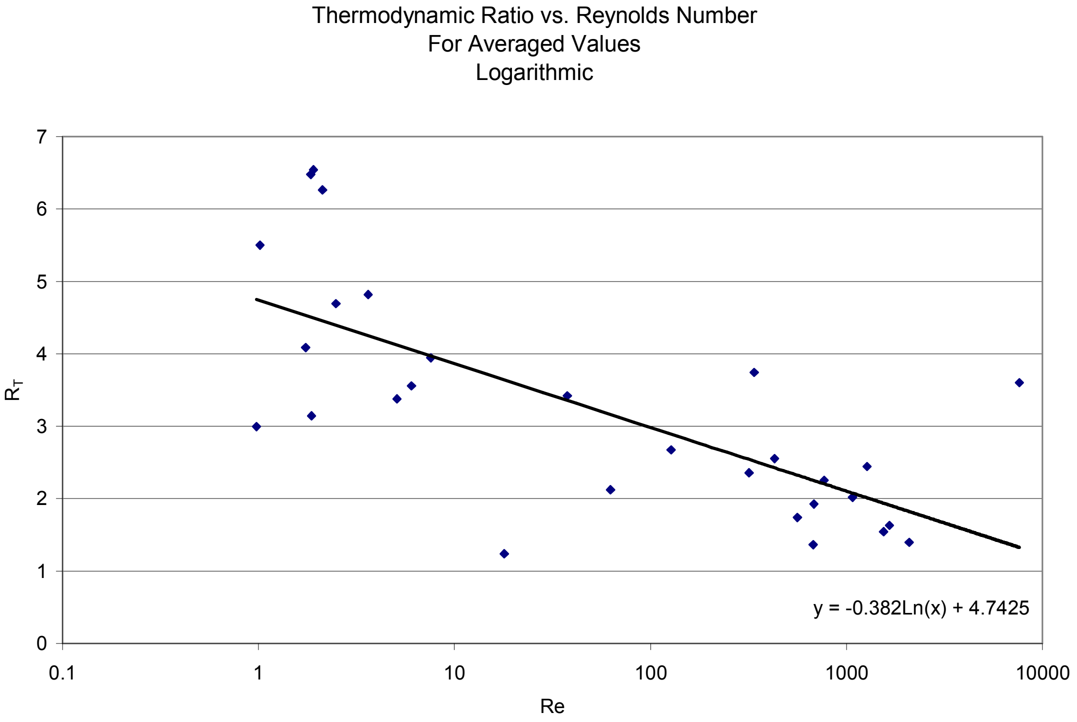

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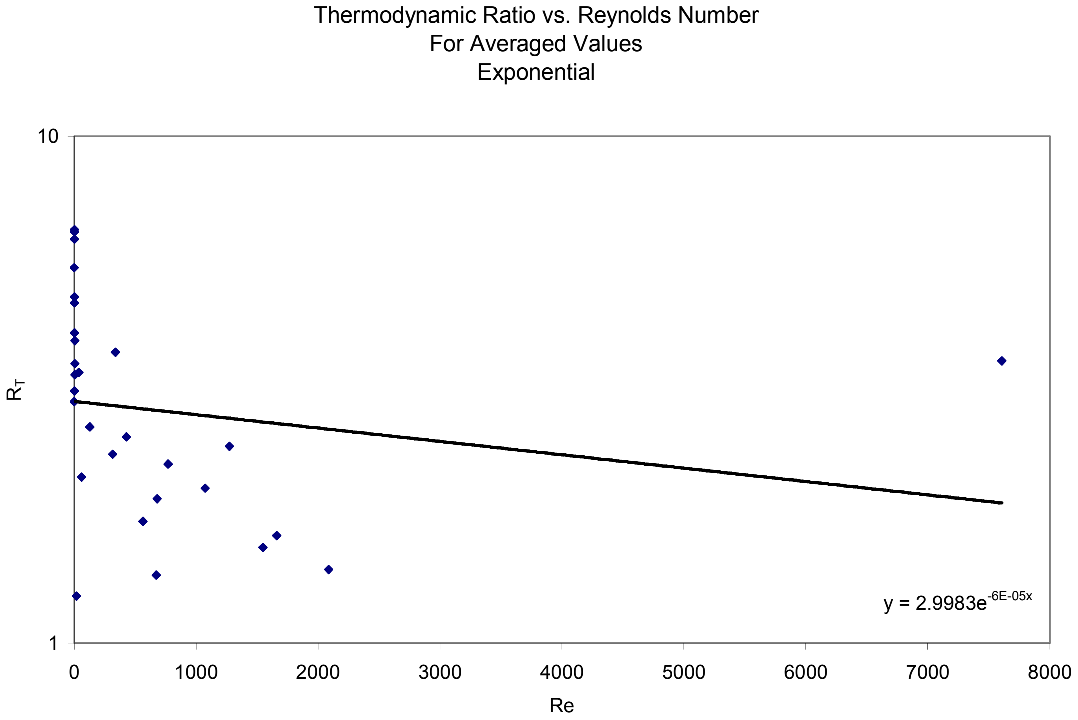

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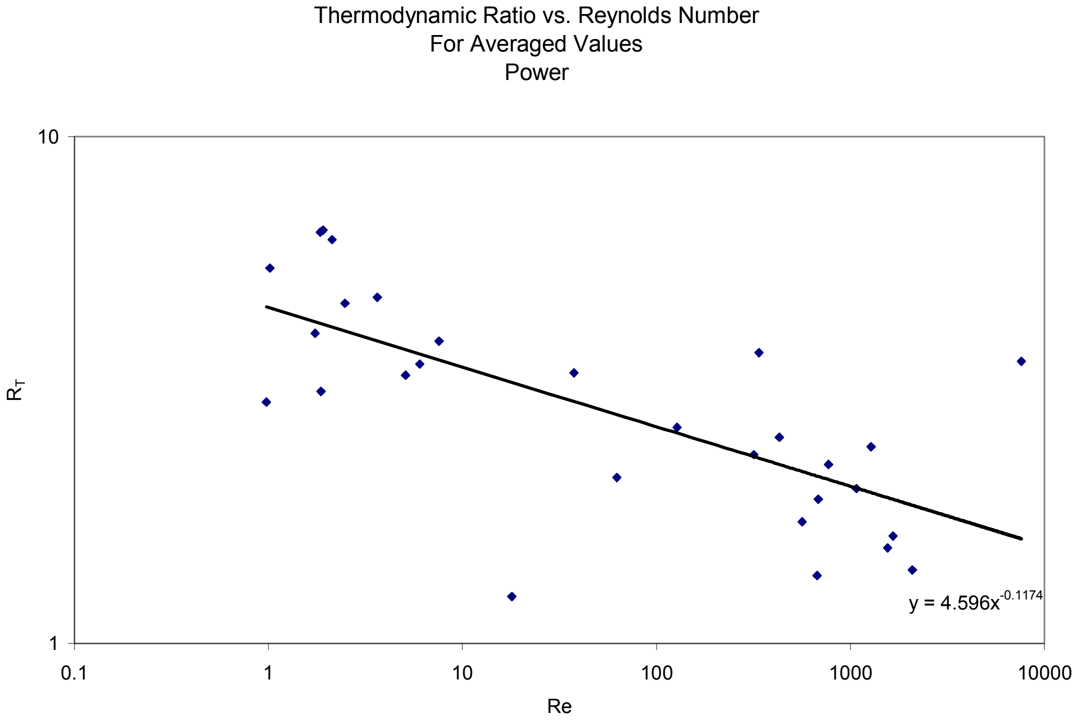

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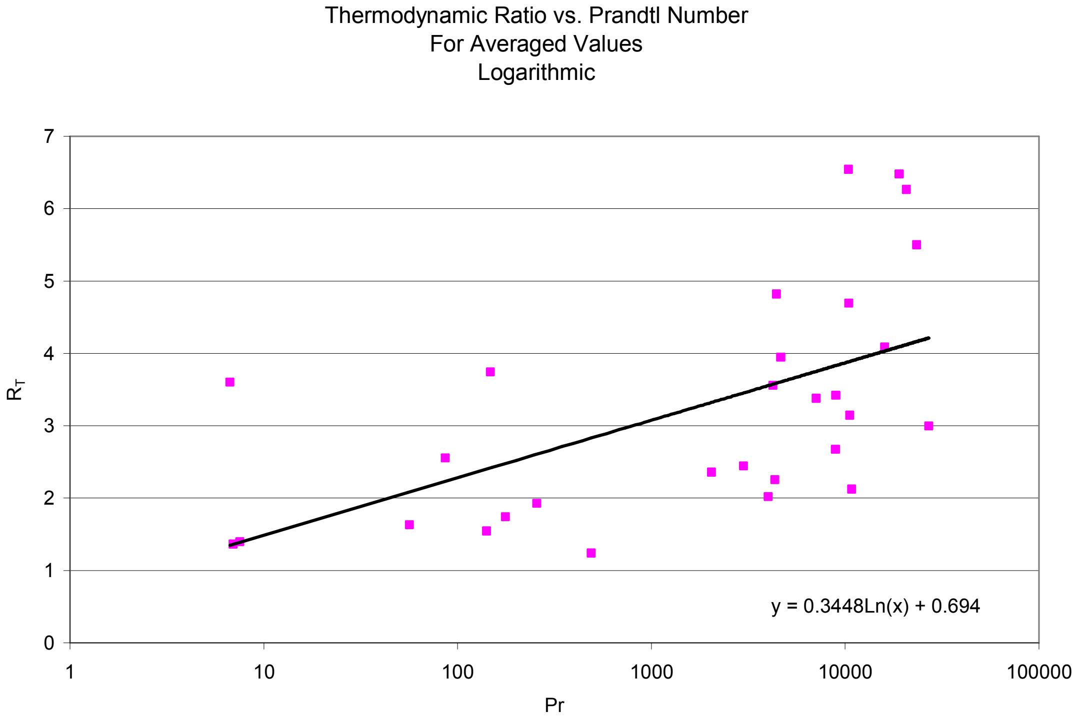

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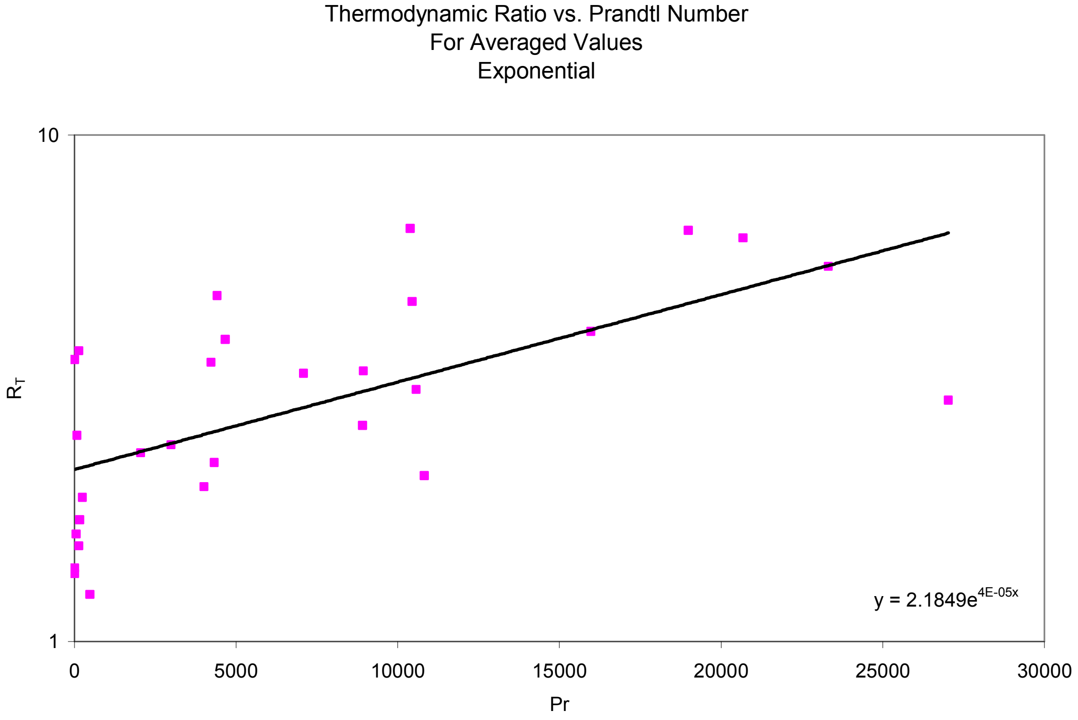

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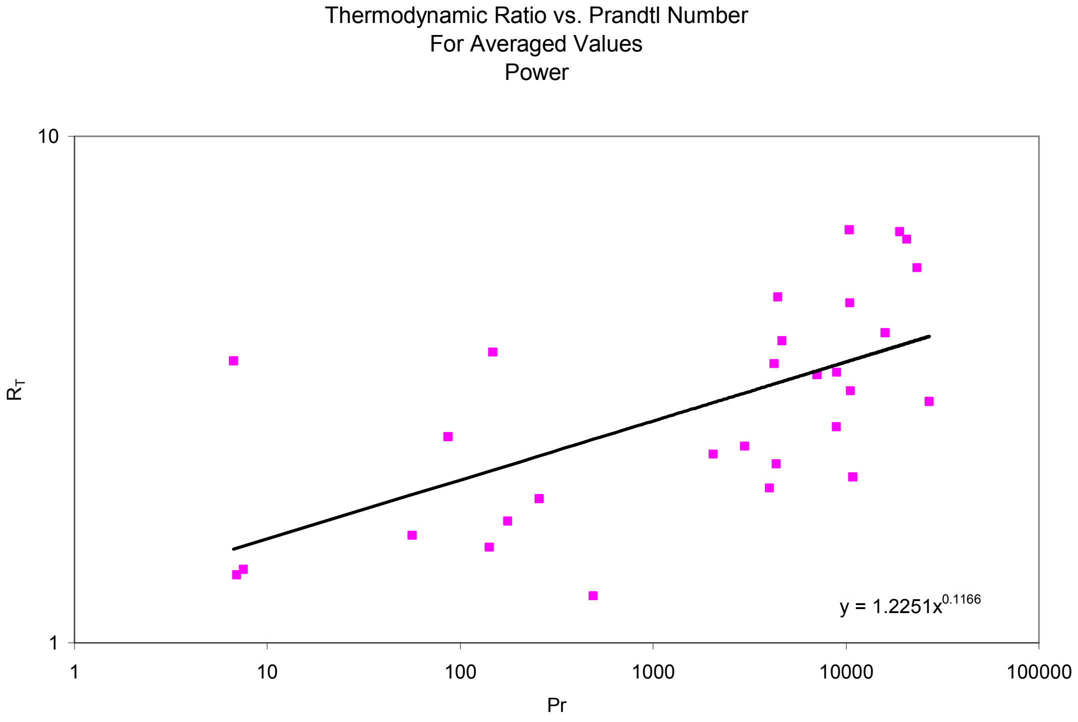

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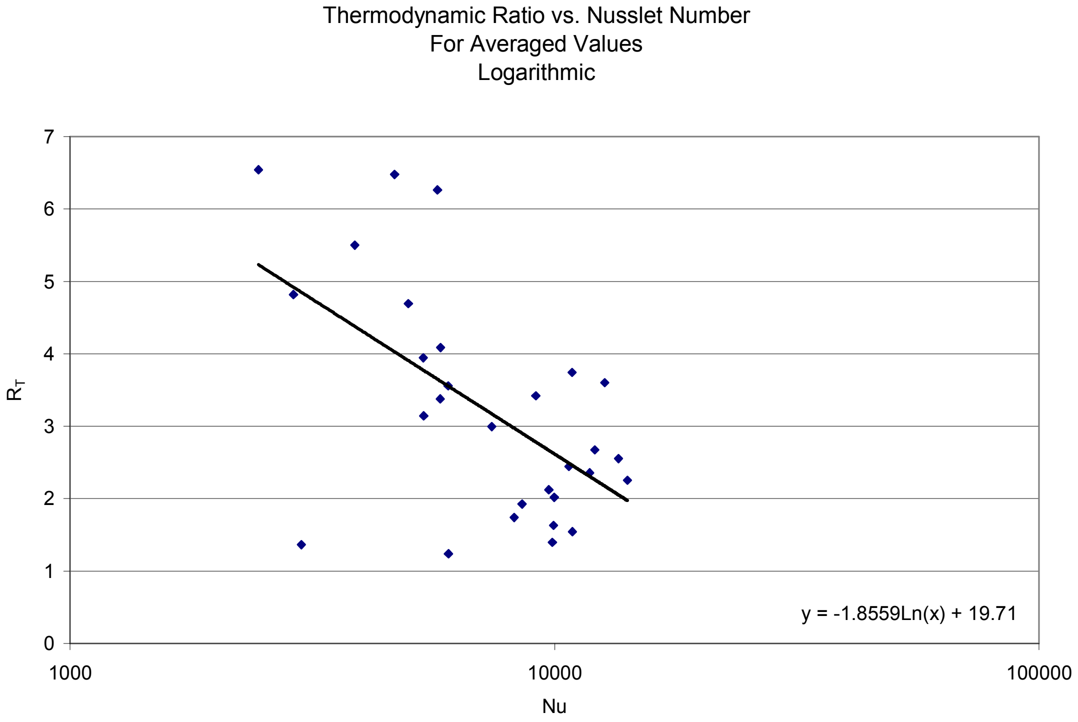

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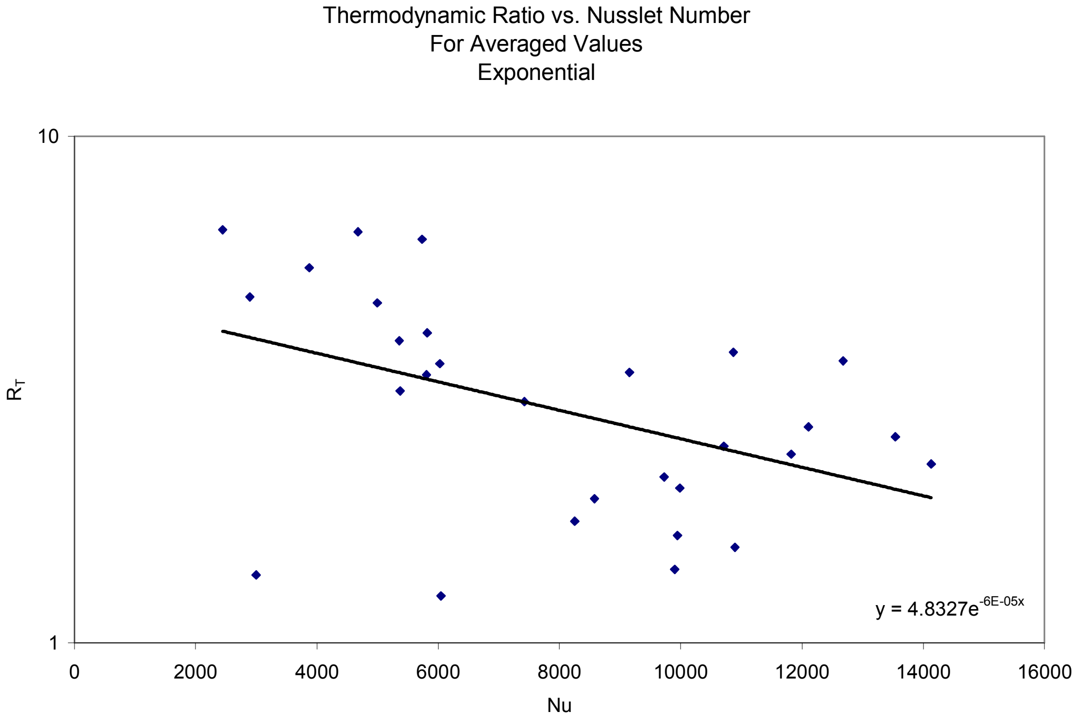

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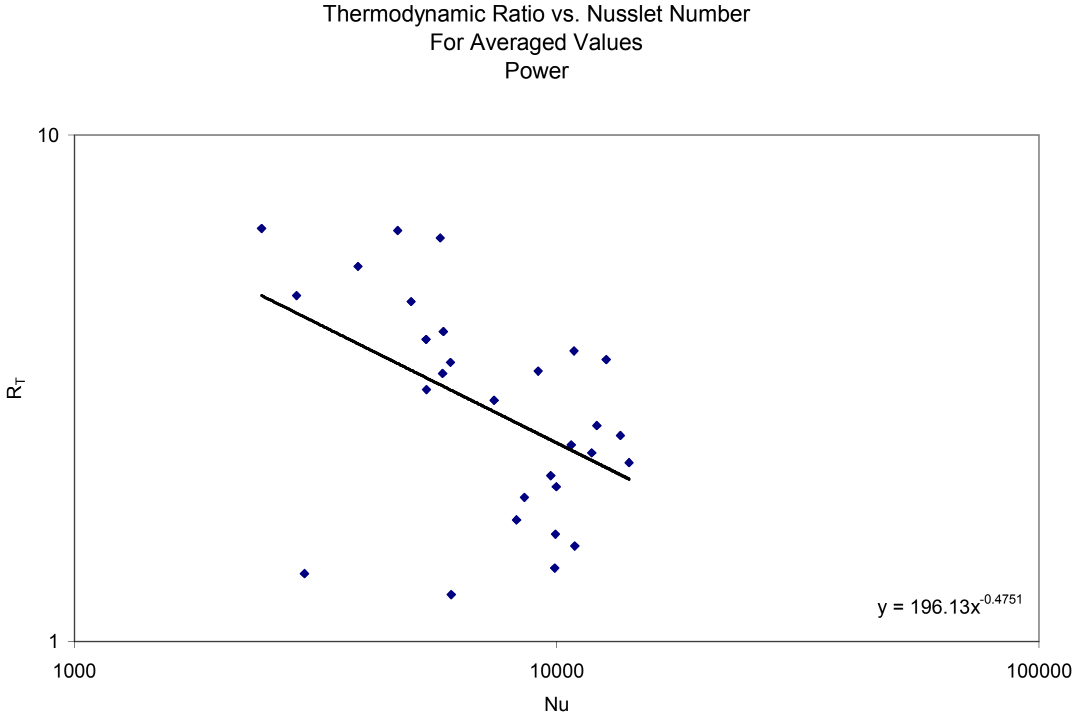

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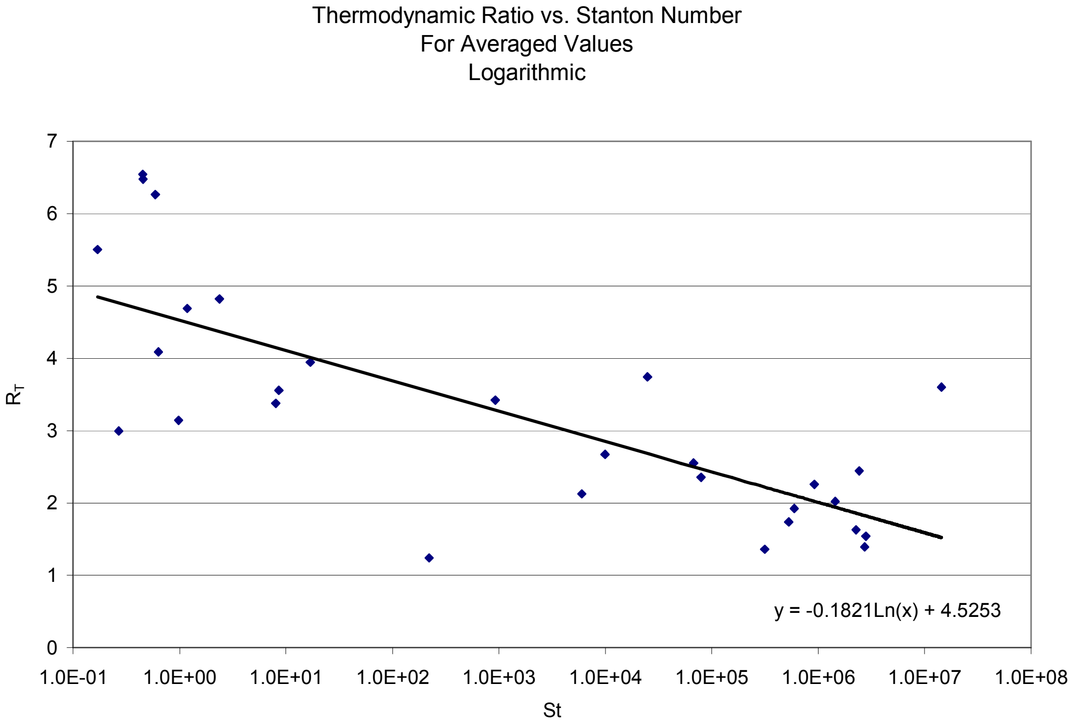

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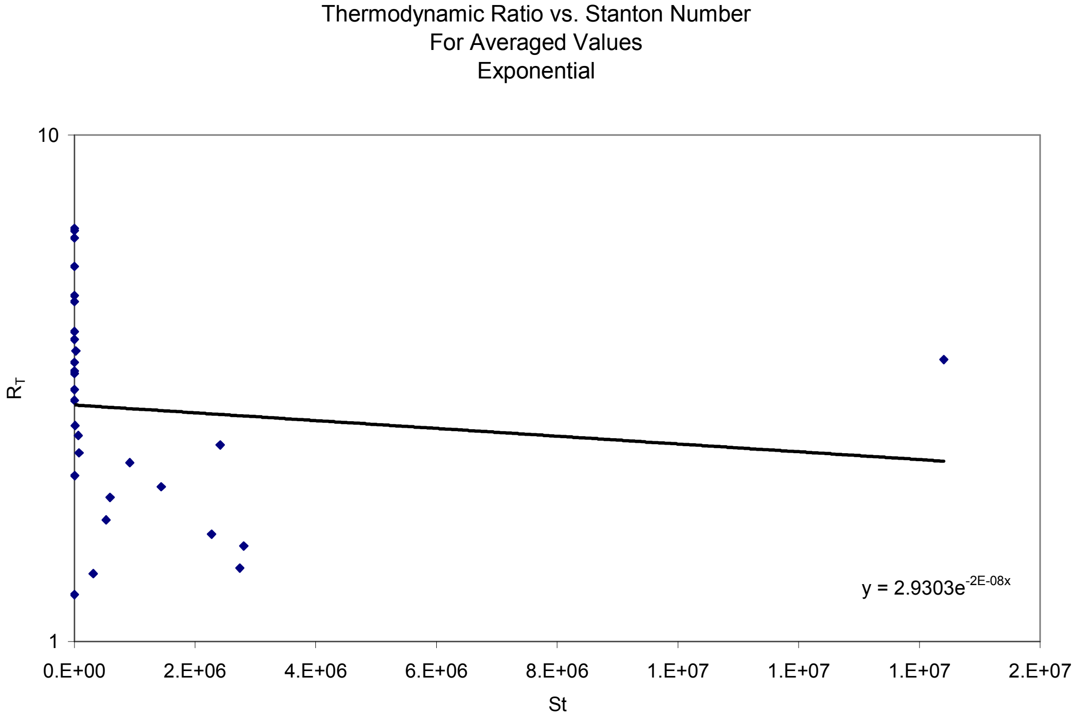

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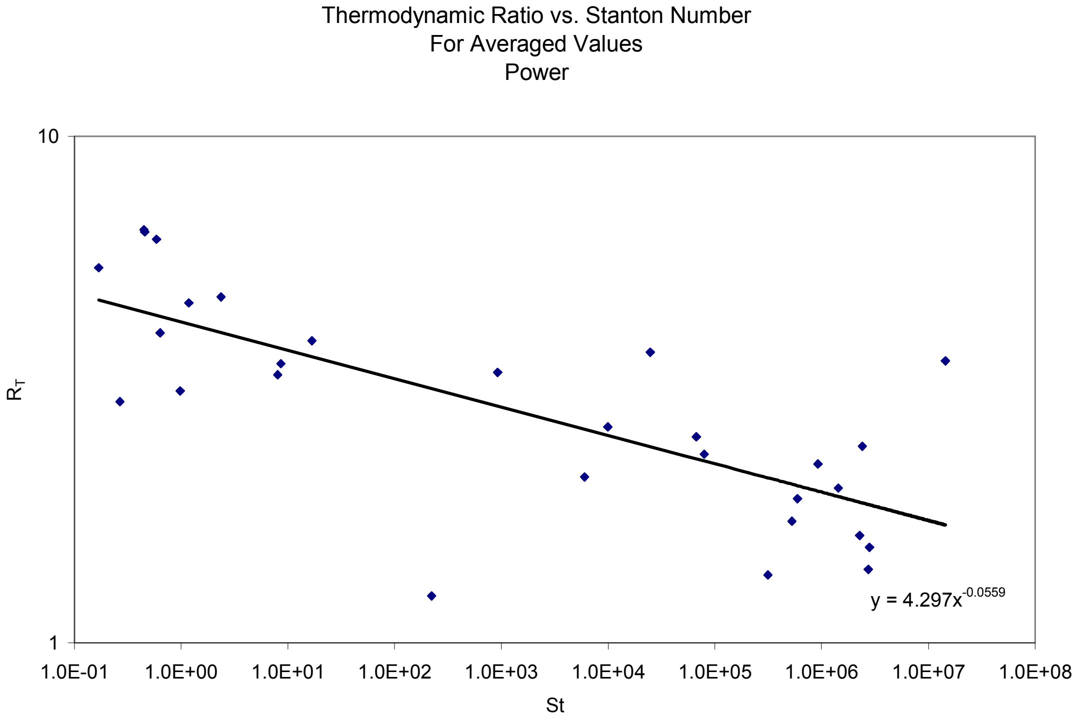

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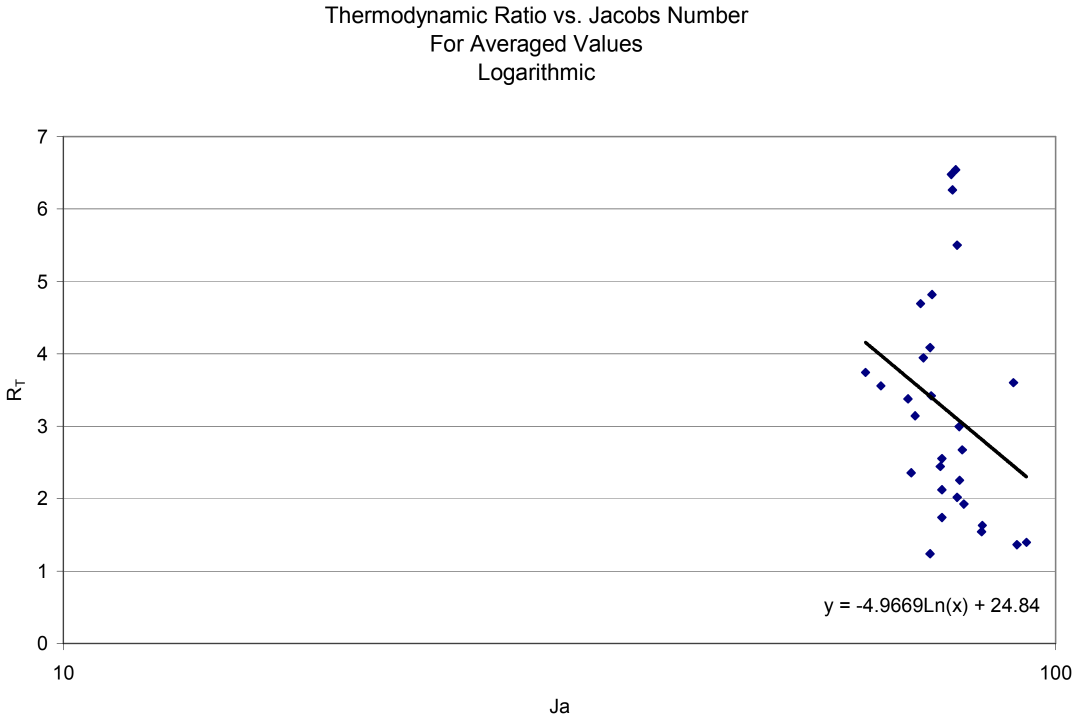

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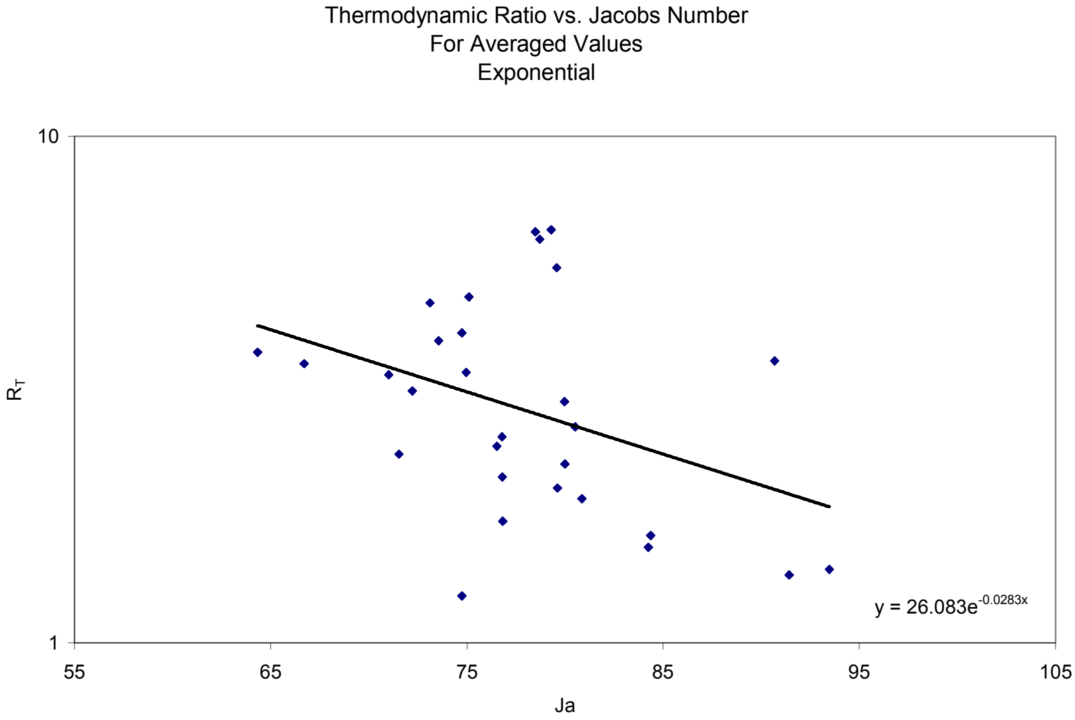

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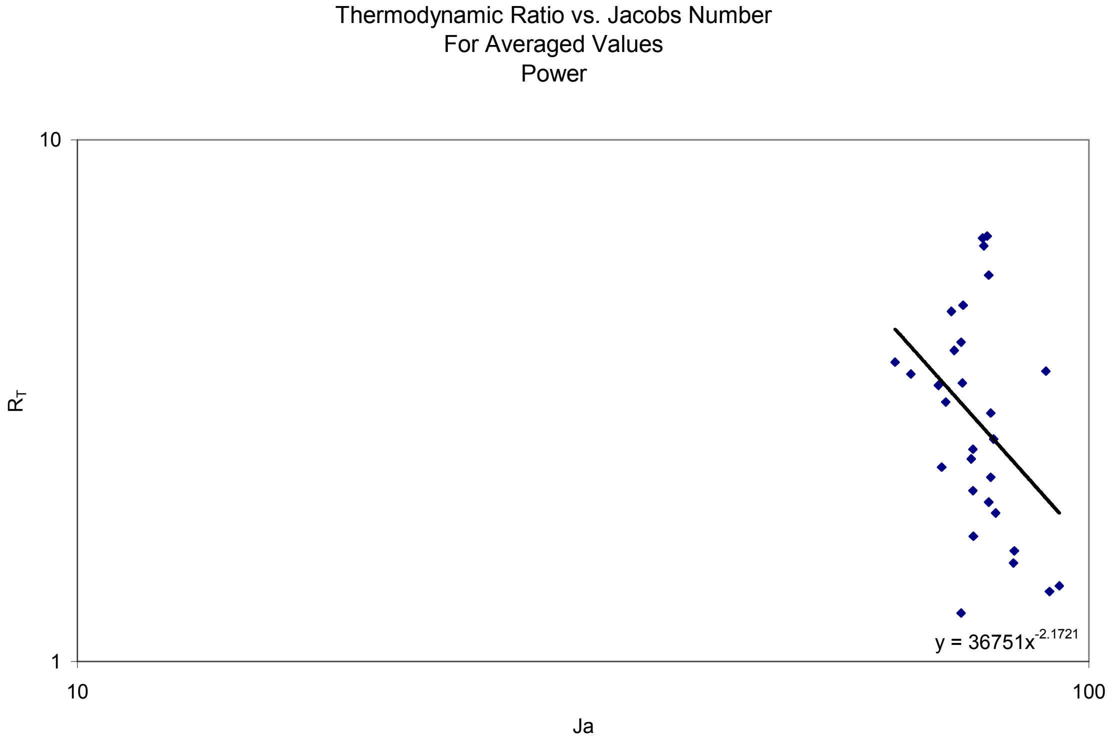


Figure G 35

APPENDIX H

RESULTS OF REGRESSION ANALYSIS FOR PORTIONS OF DATA SET

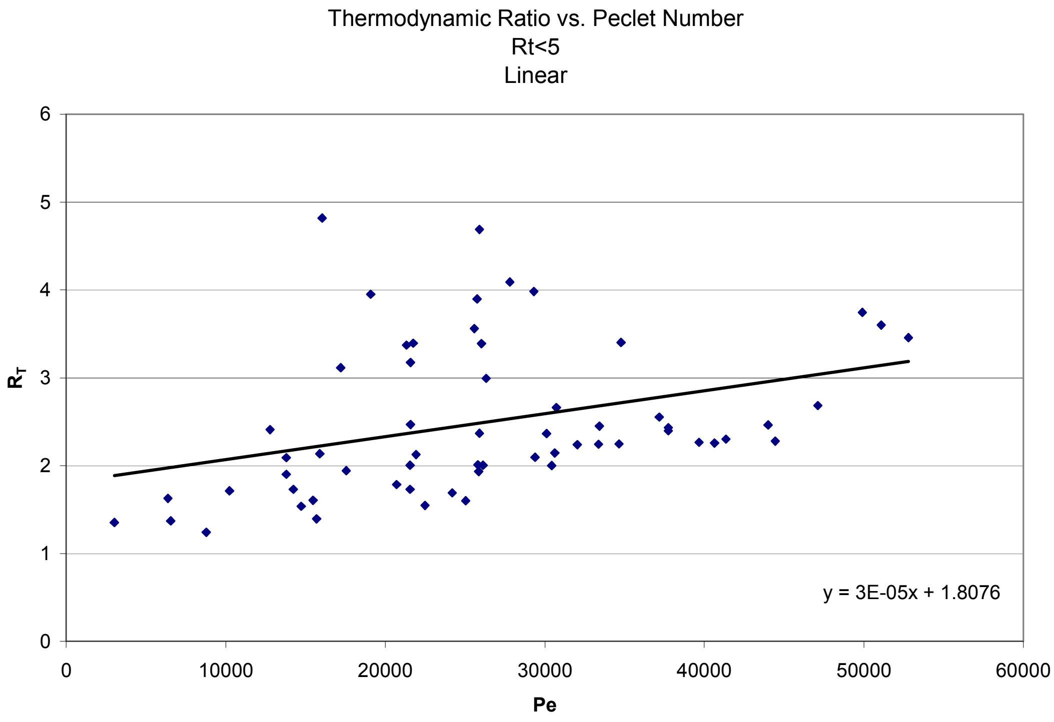
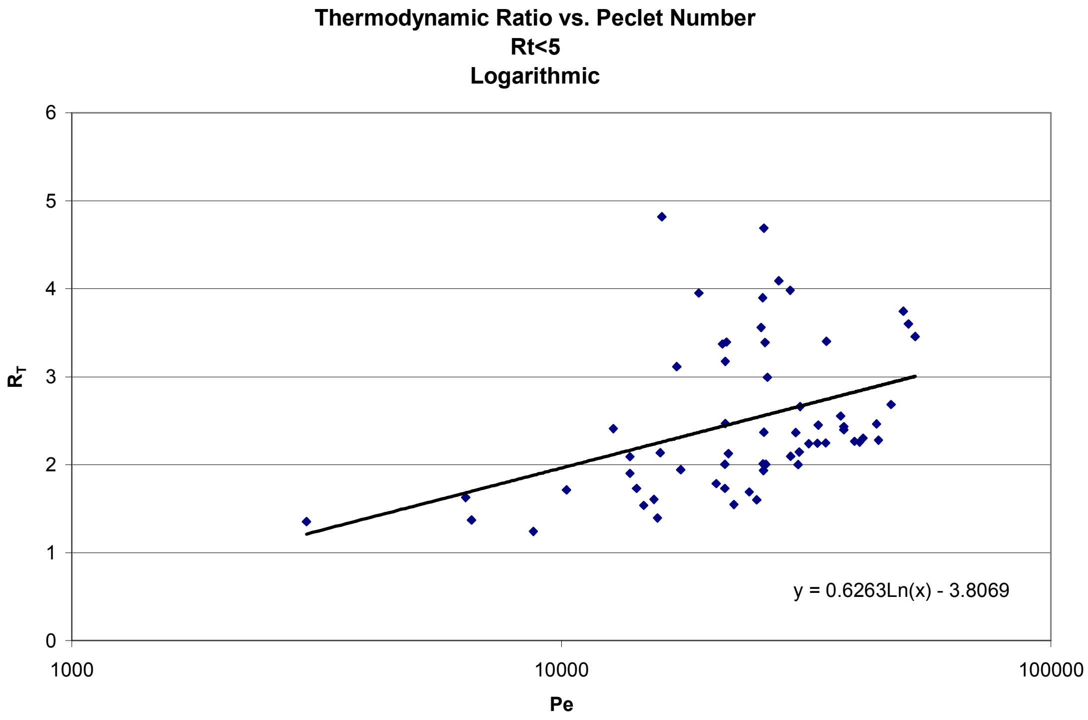


Figure H 2



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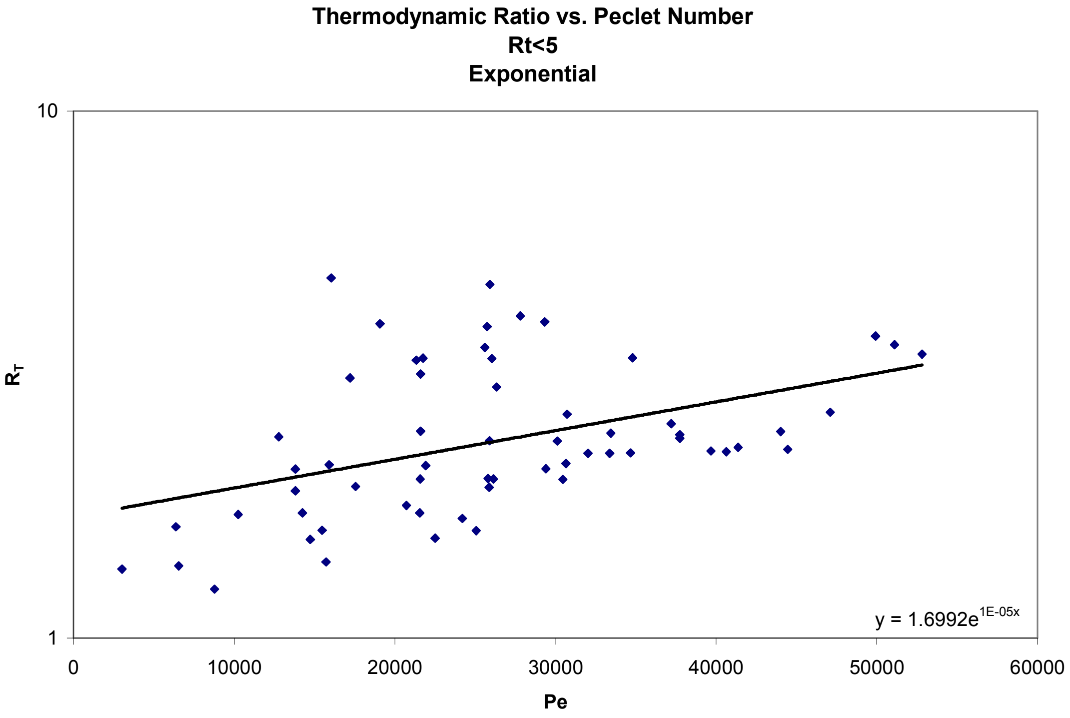

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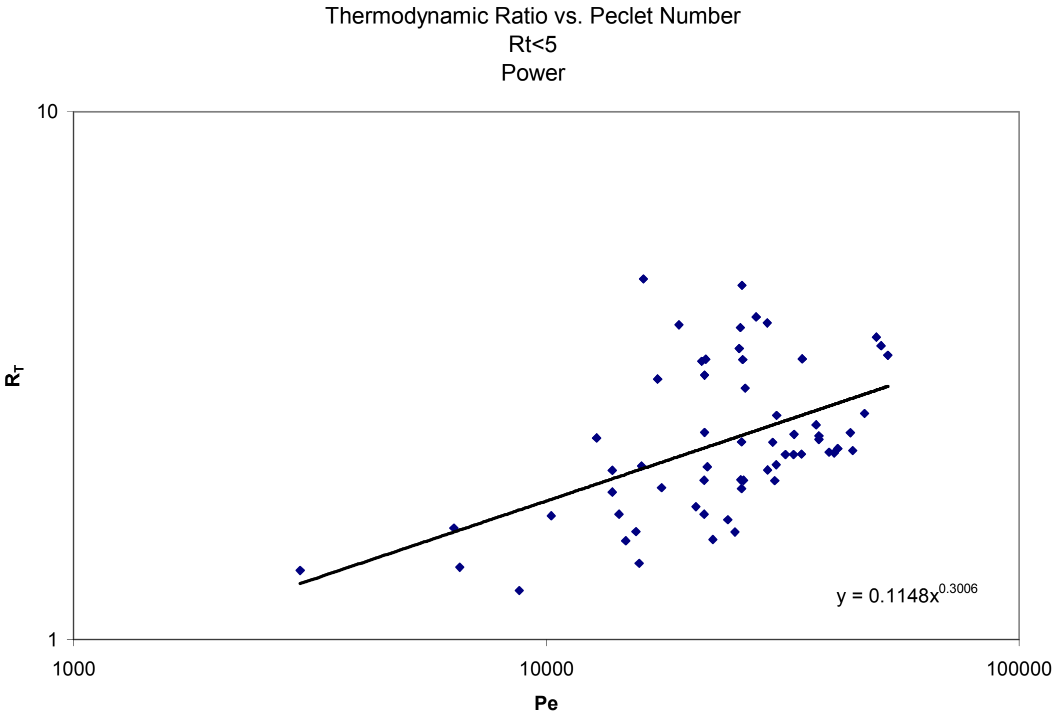

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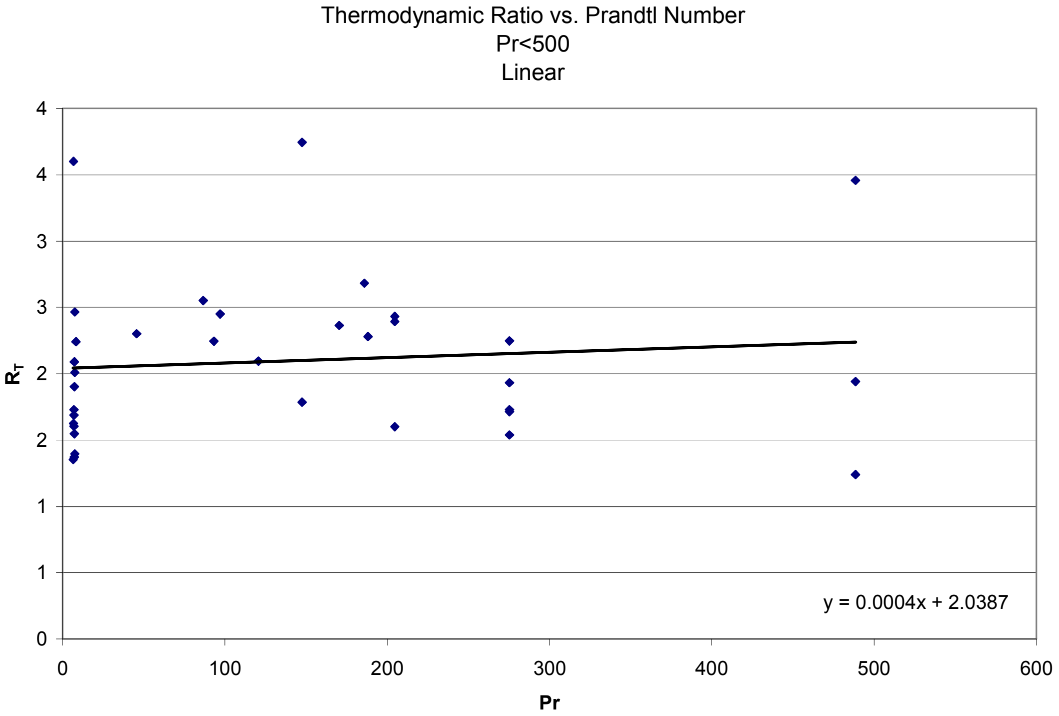

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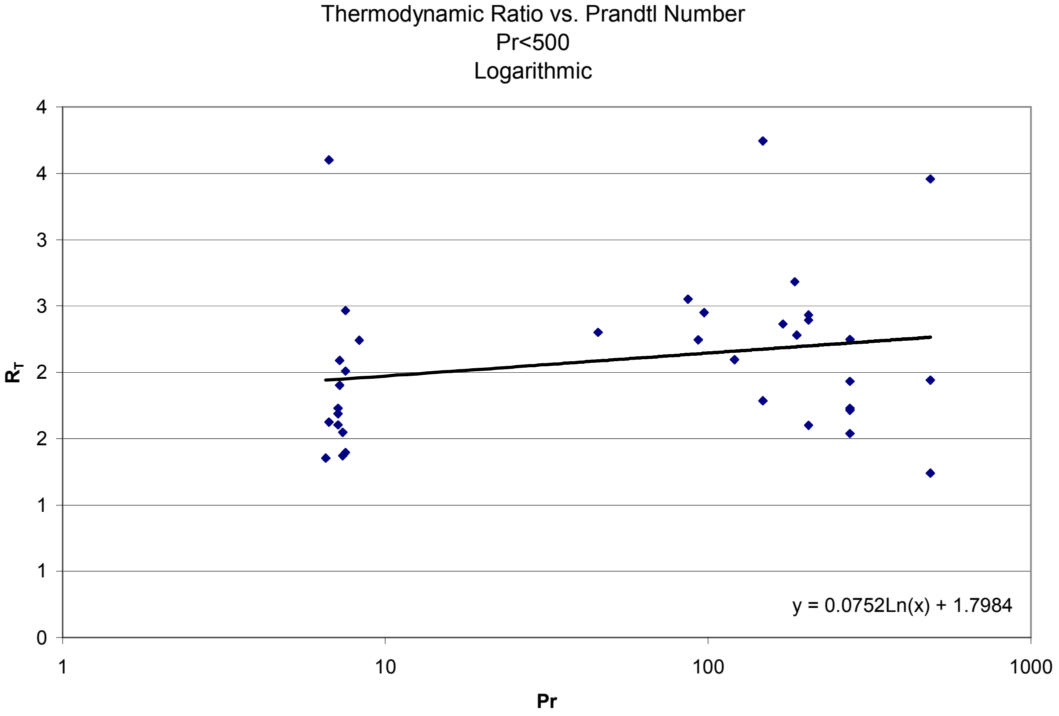

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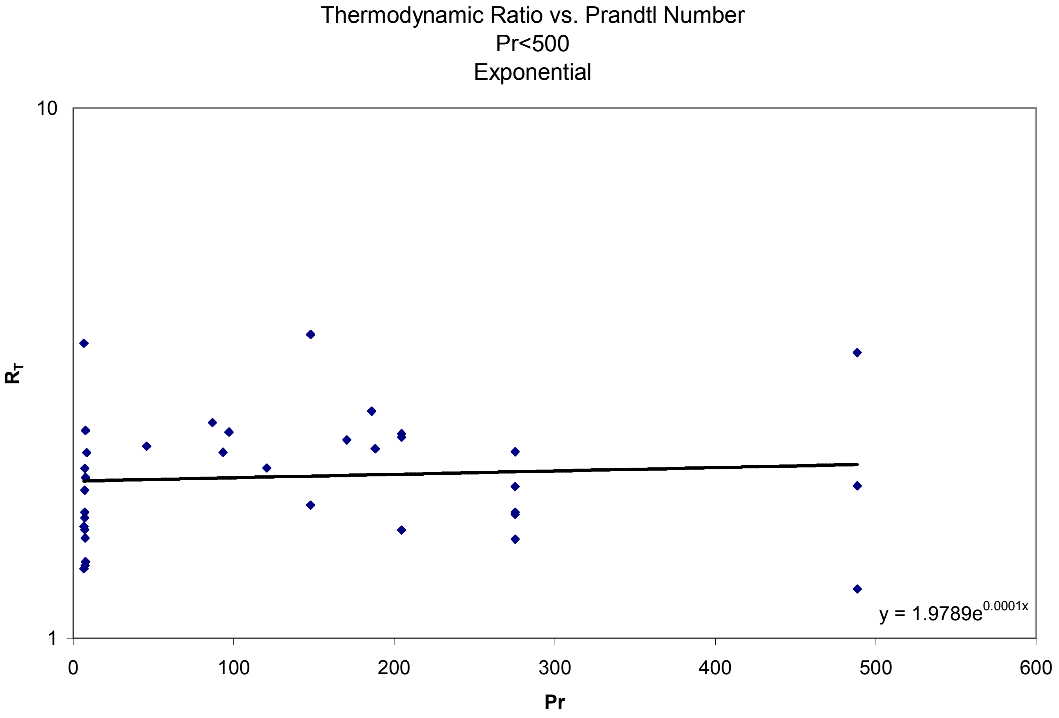

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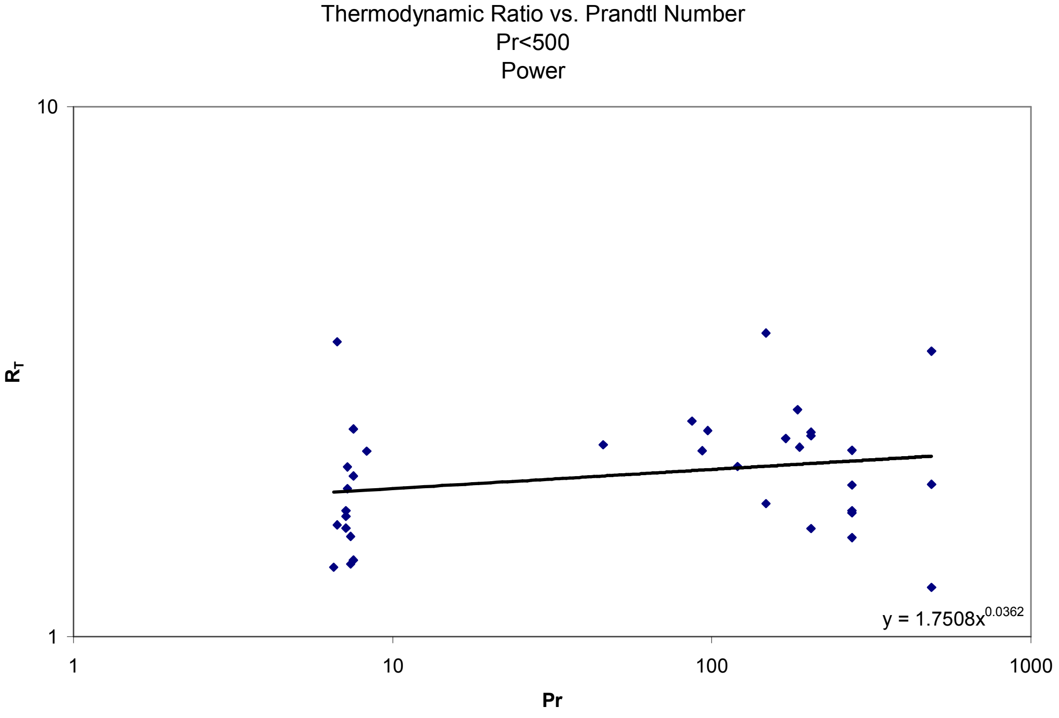

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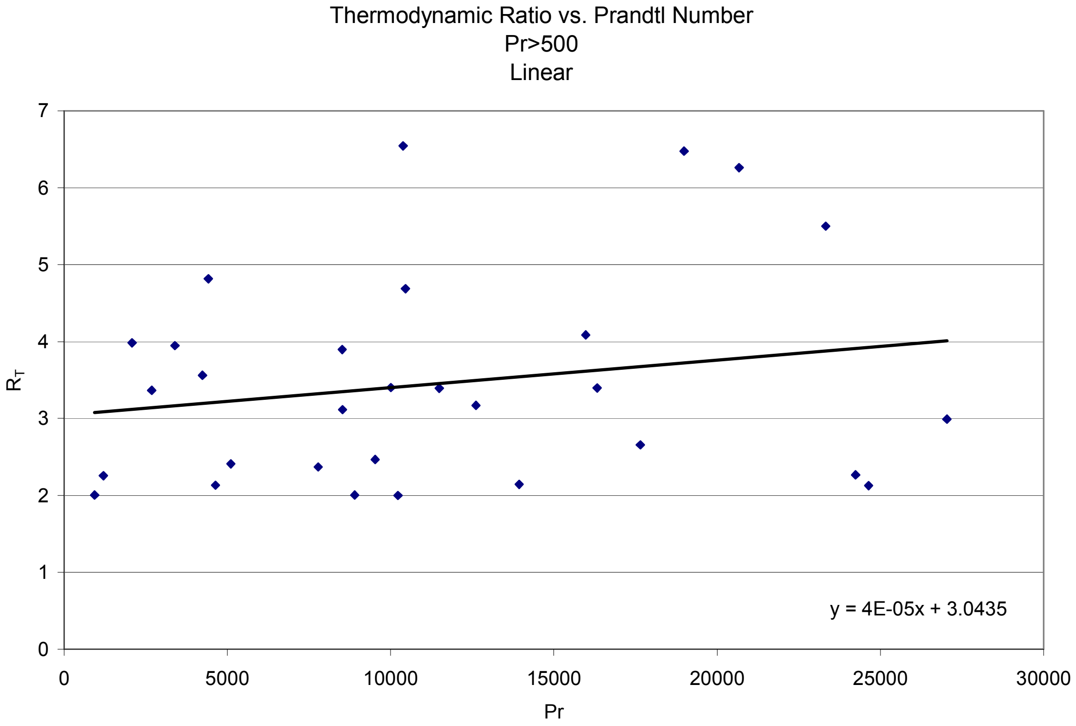

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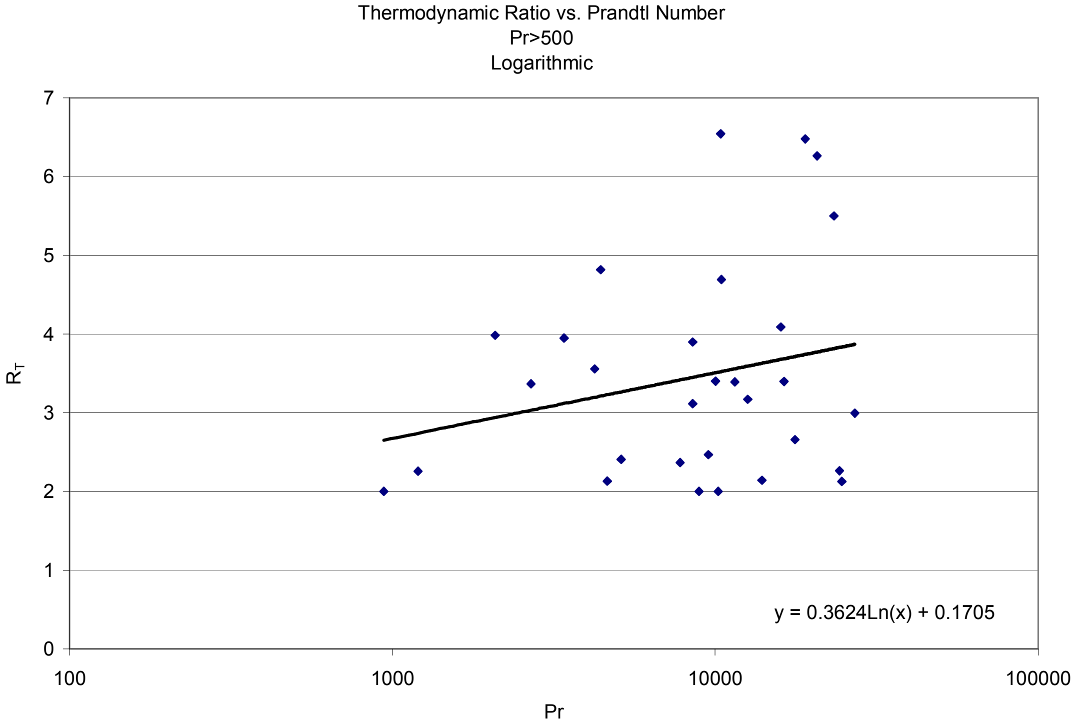

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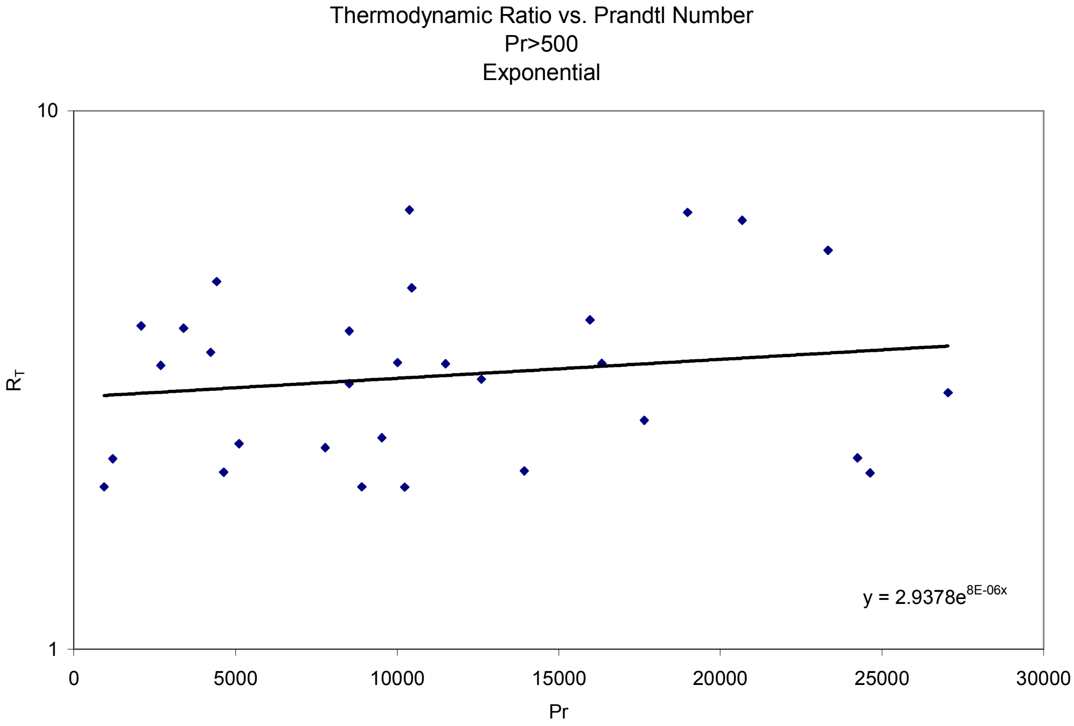

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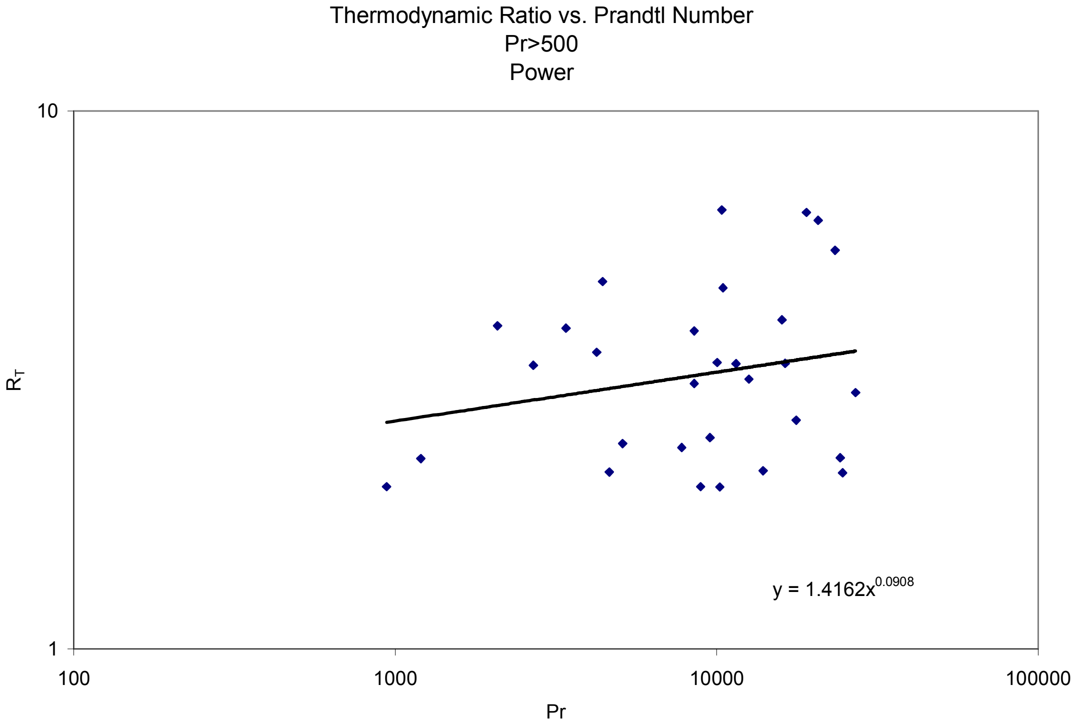

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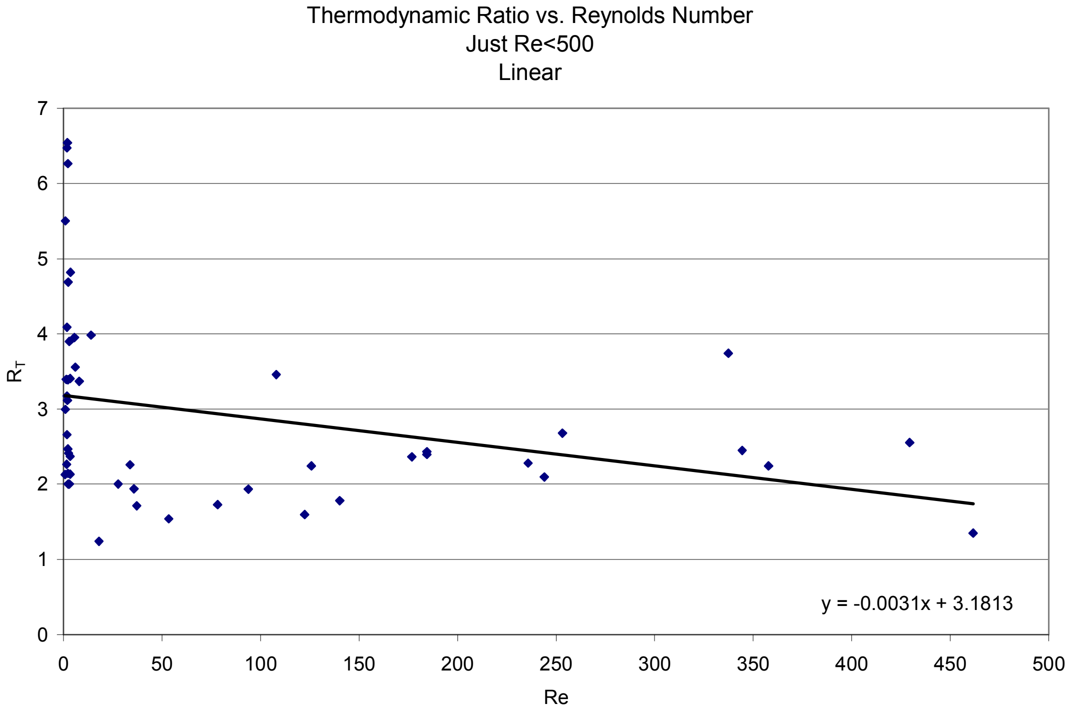

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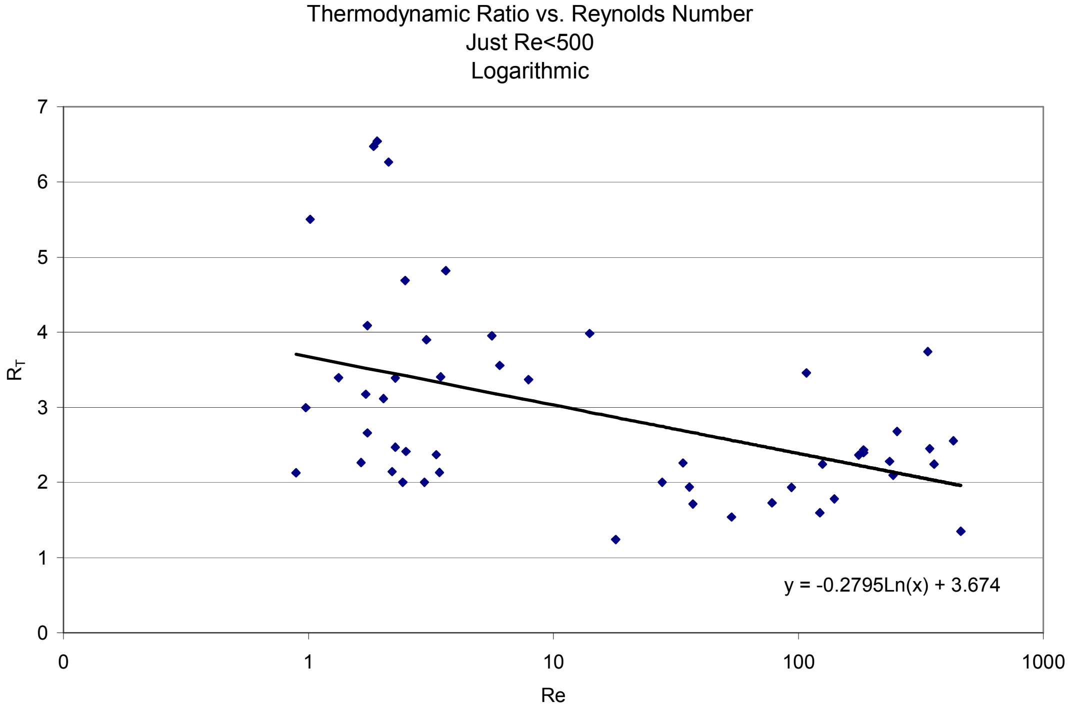

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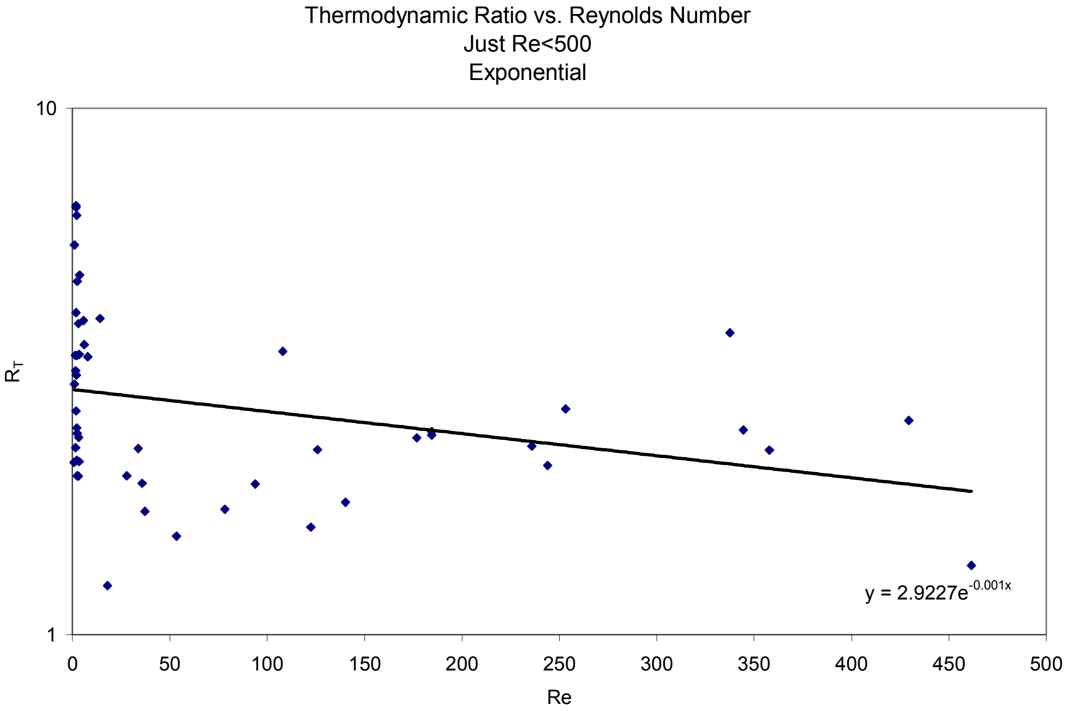

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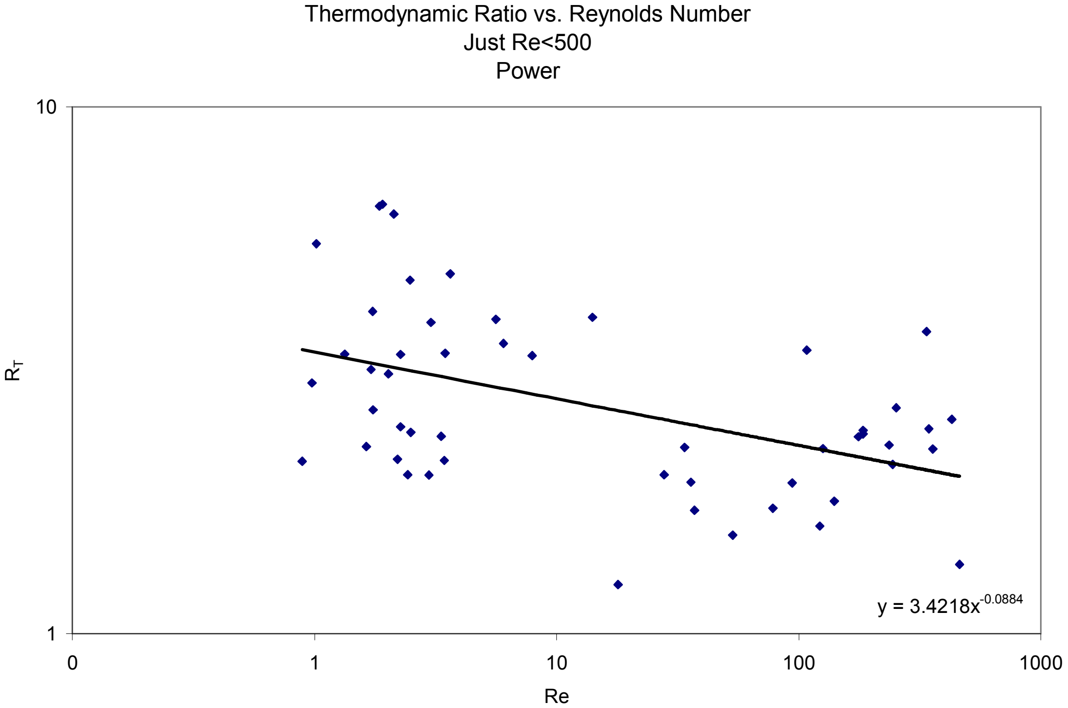

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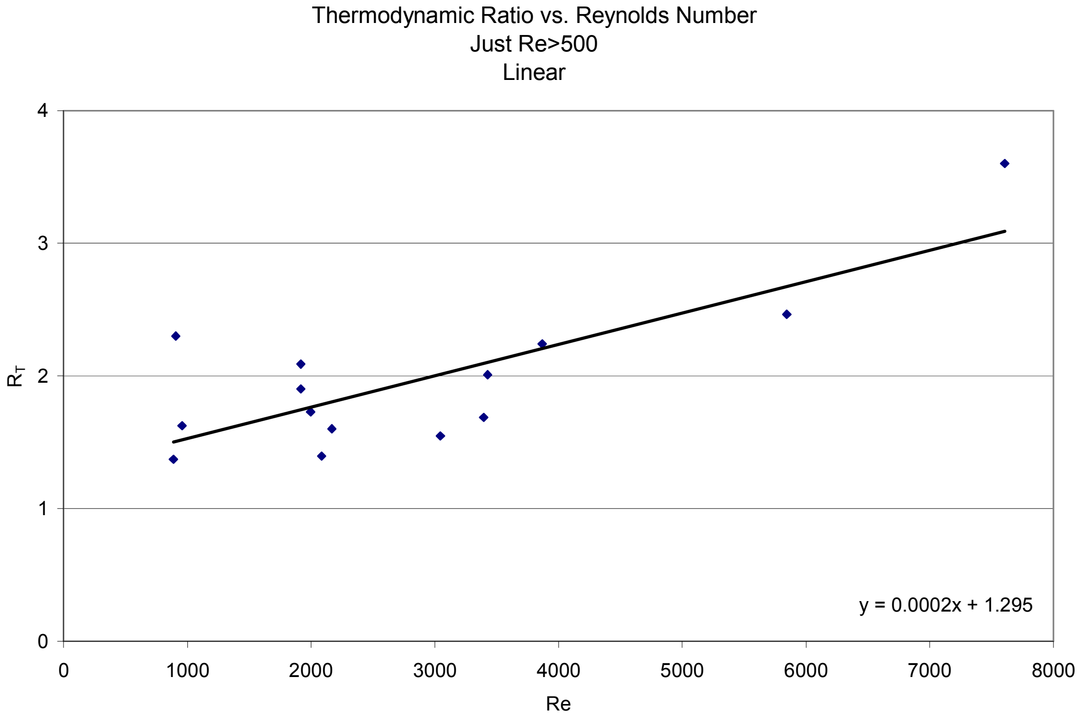

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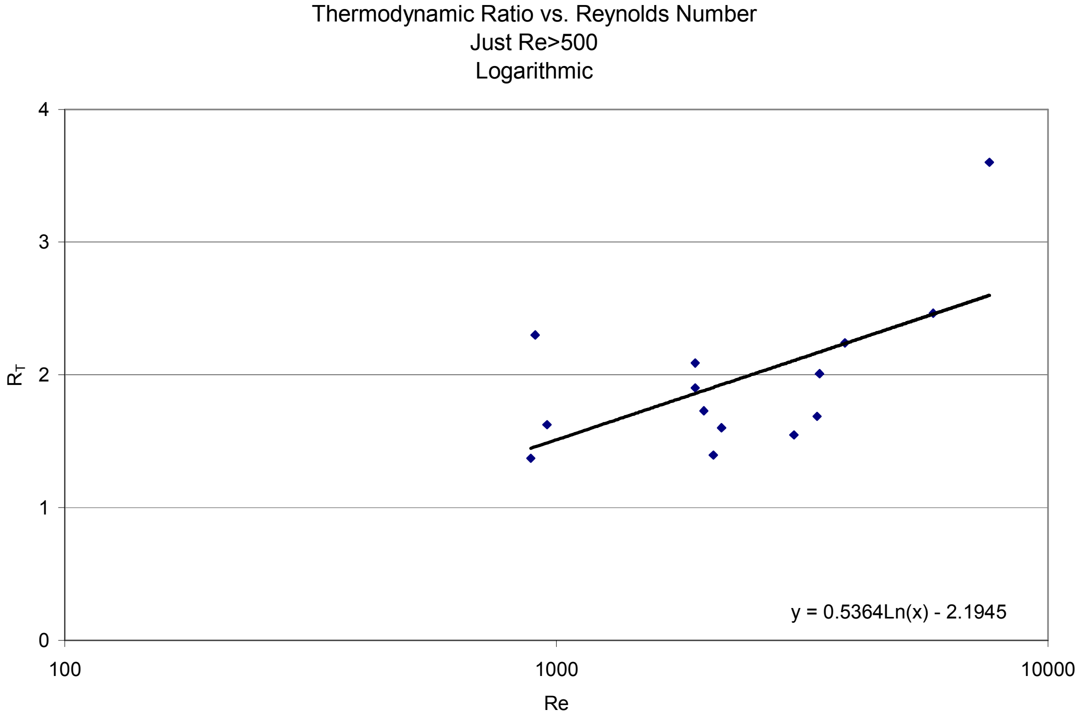

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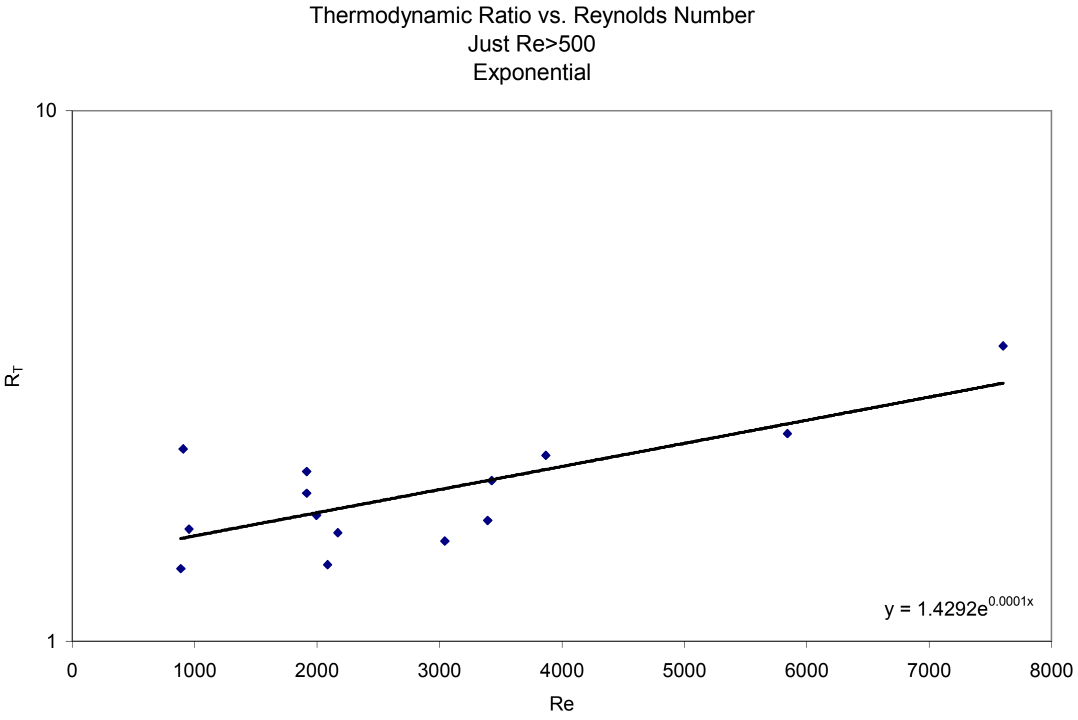

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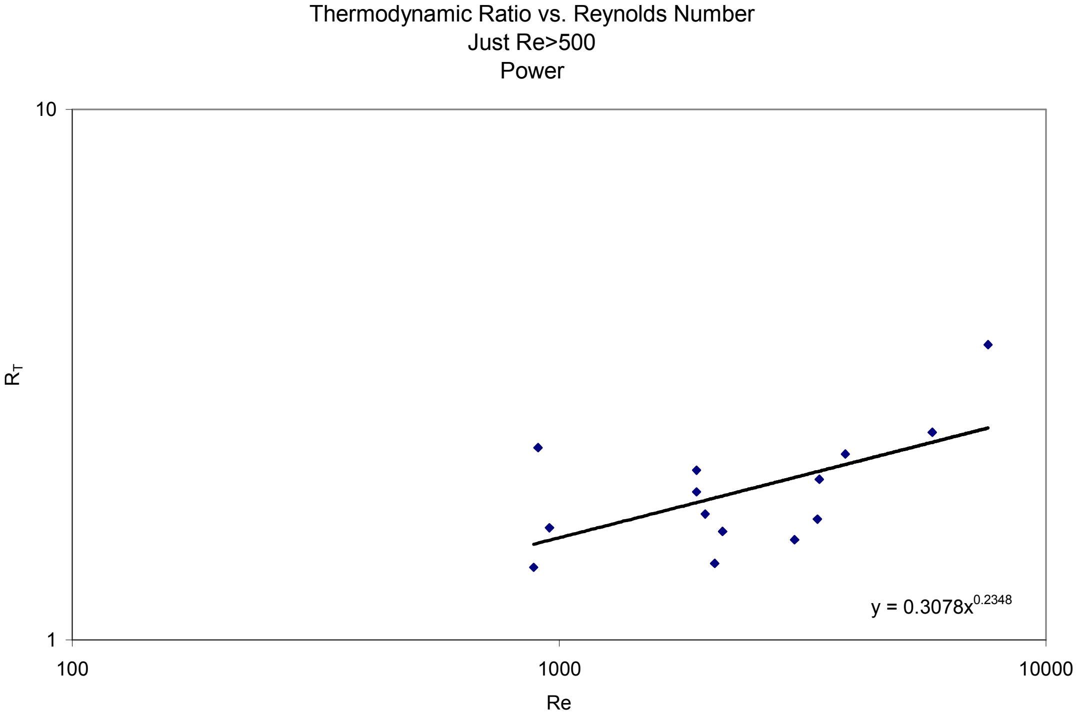

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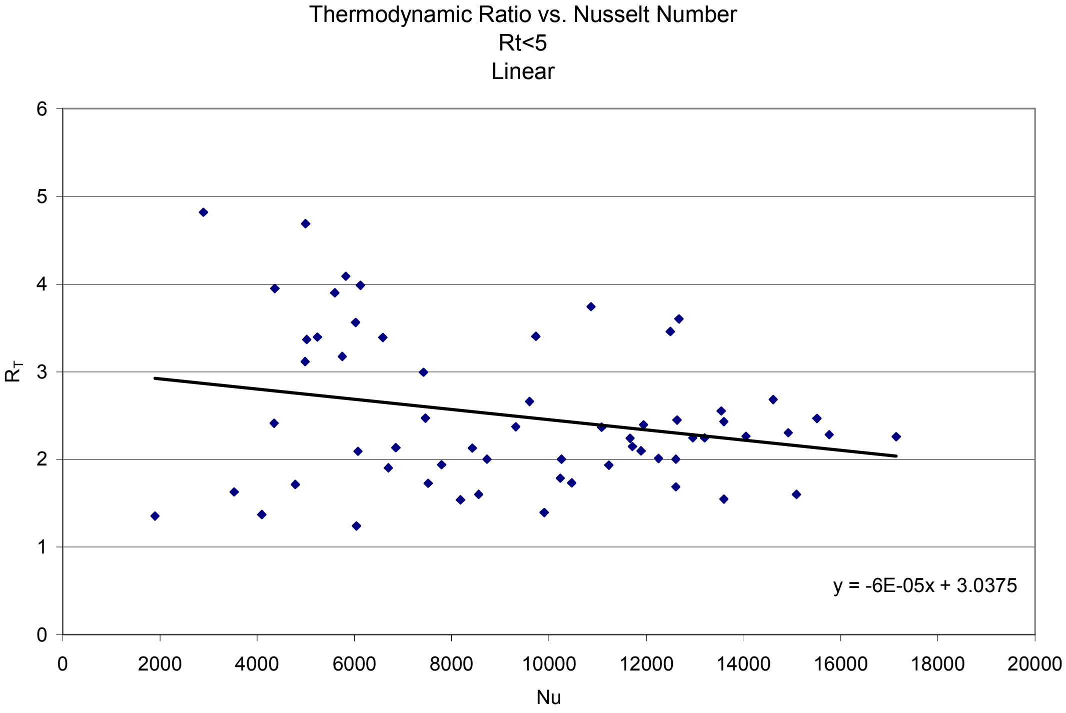

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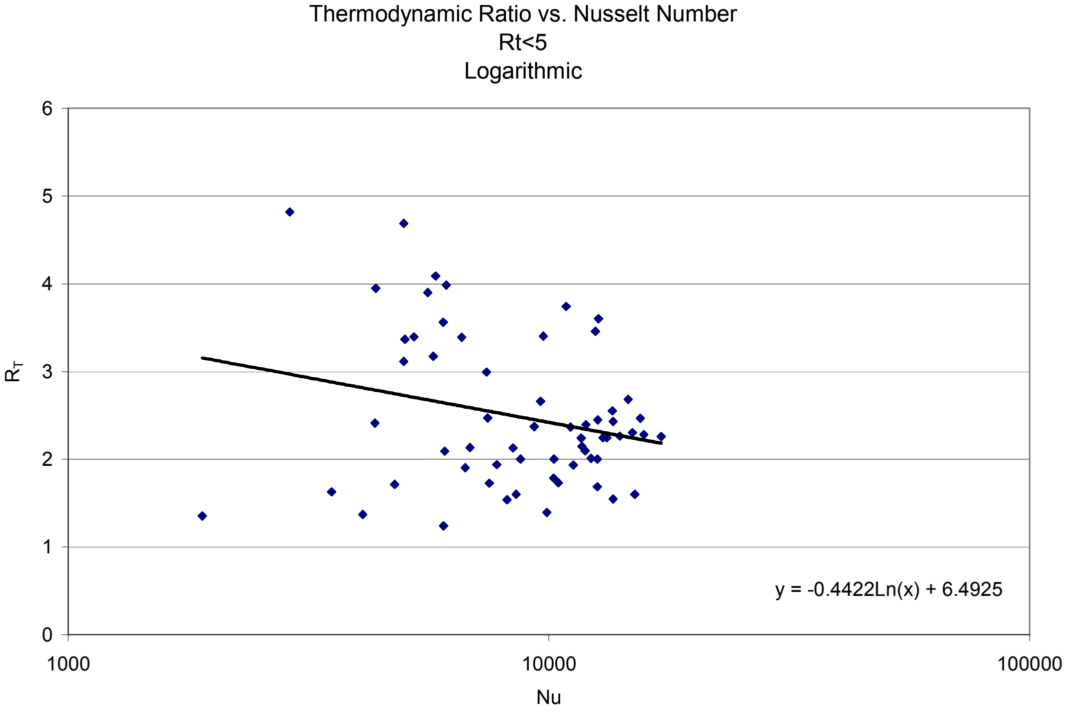

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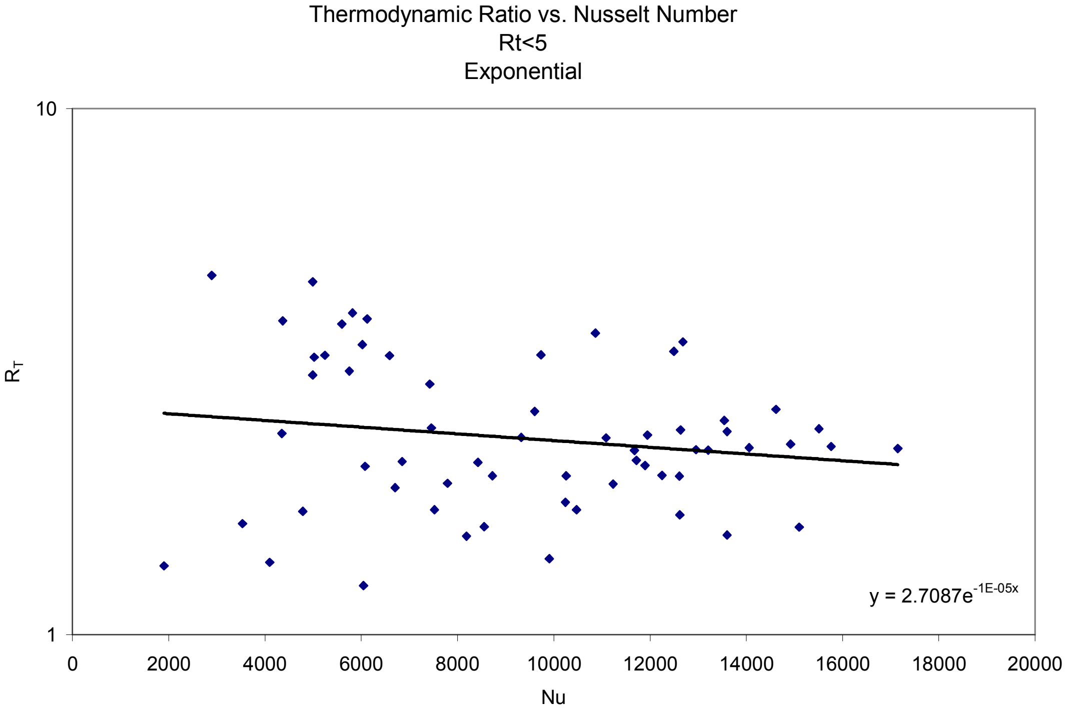

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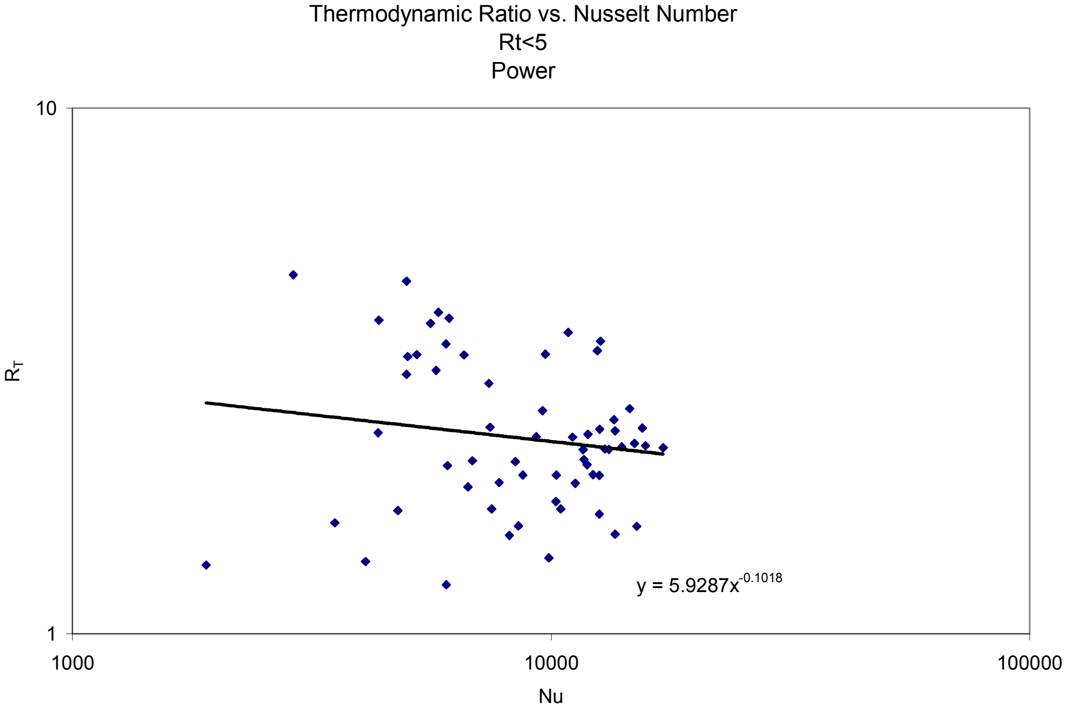

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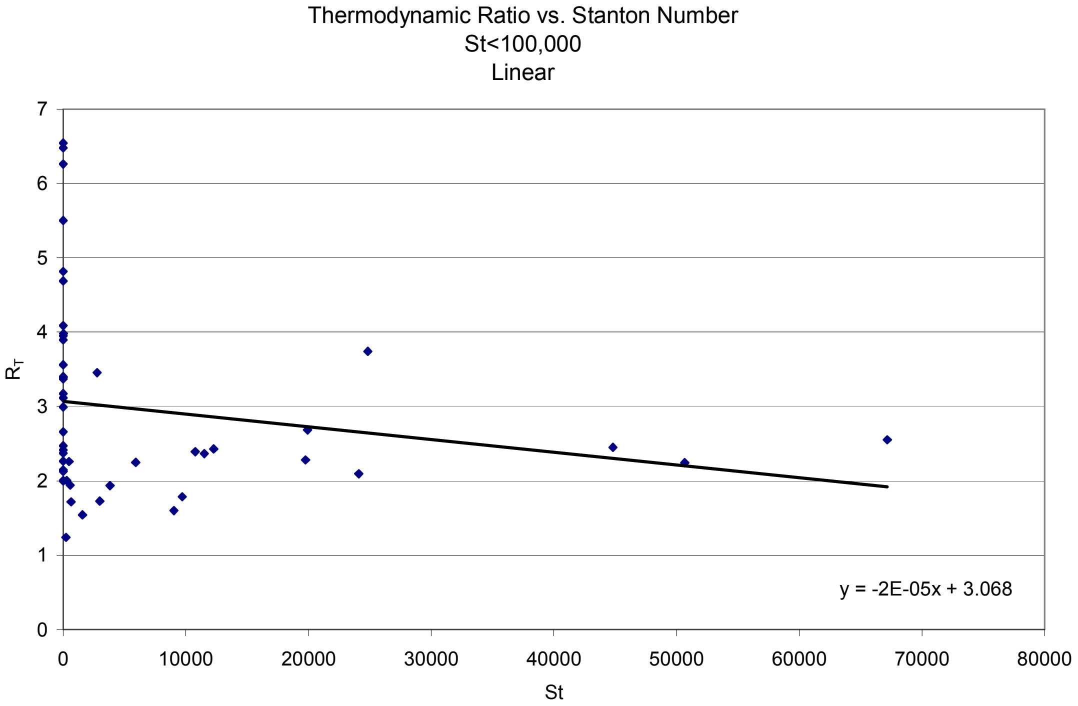

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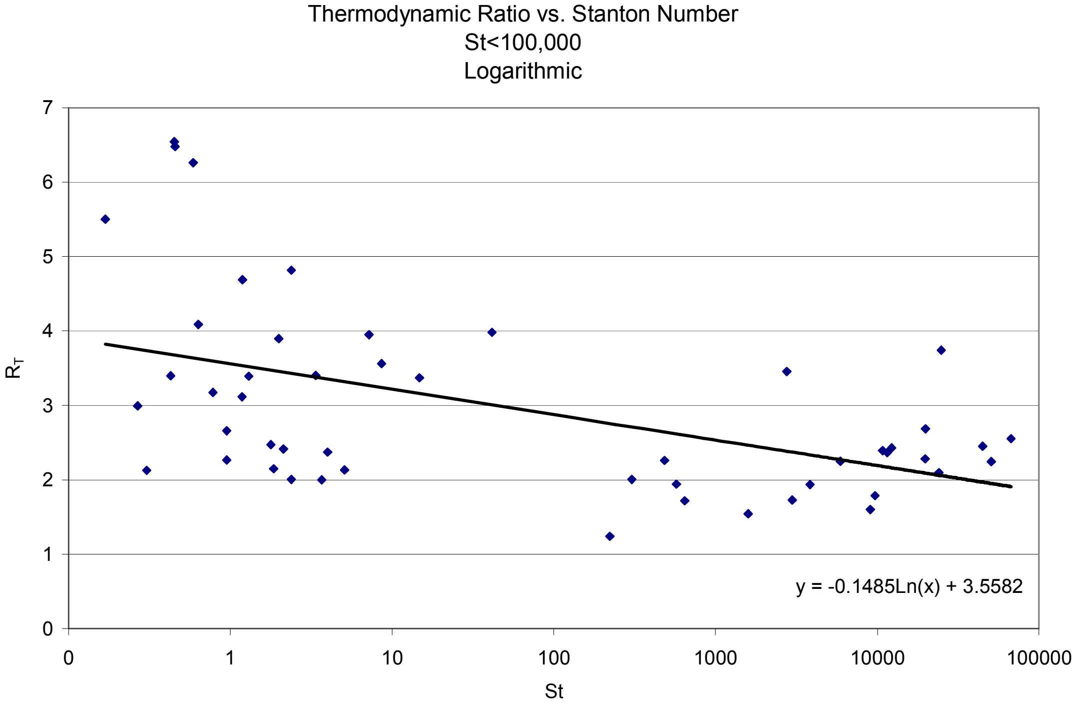

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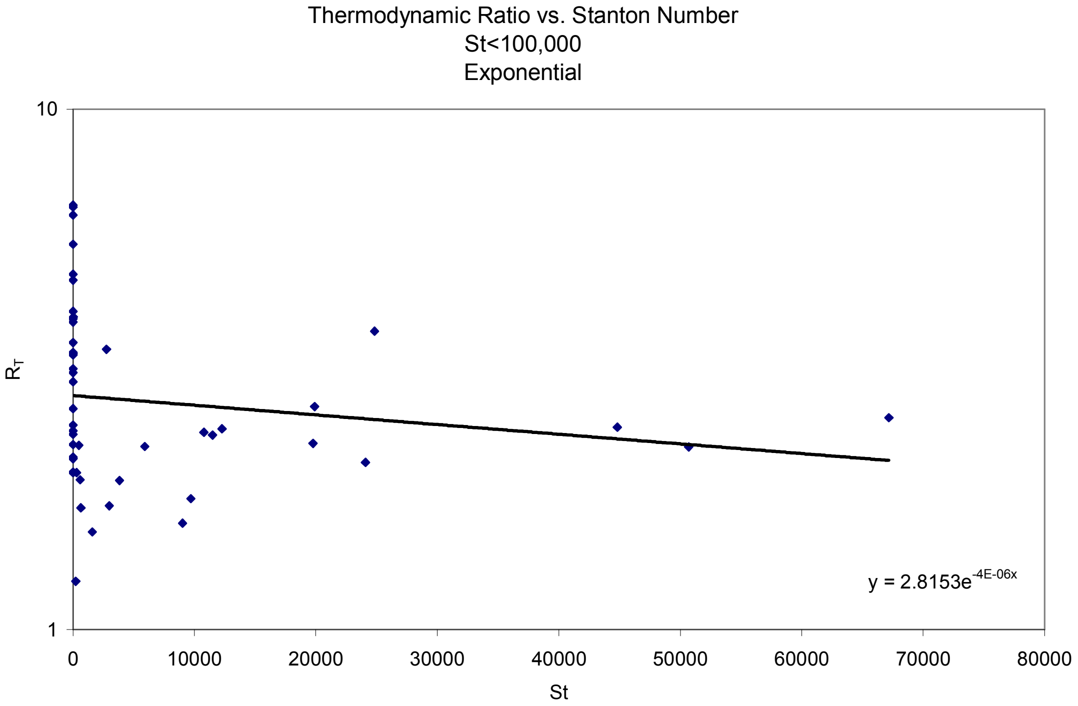

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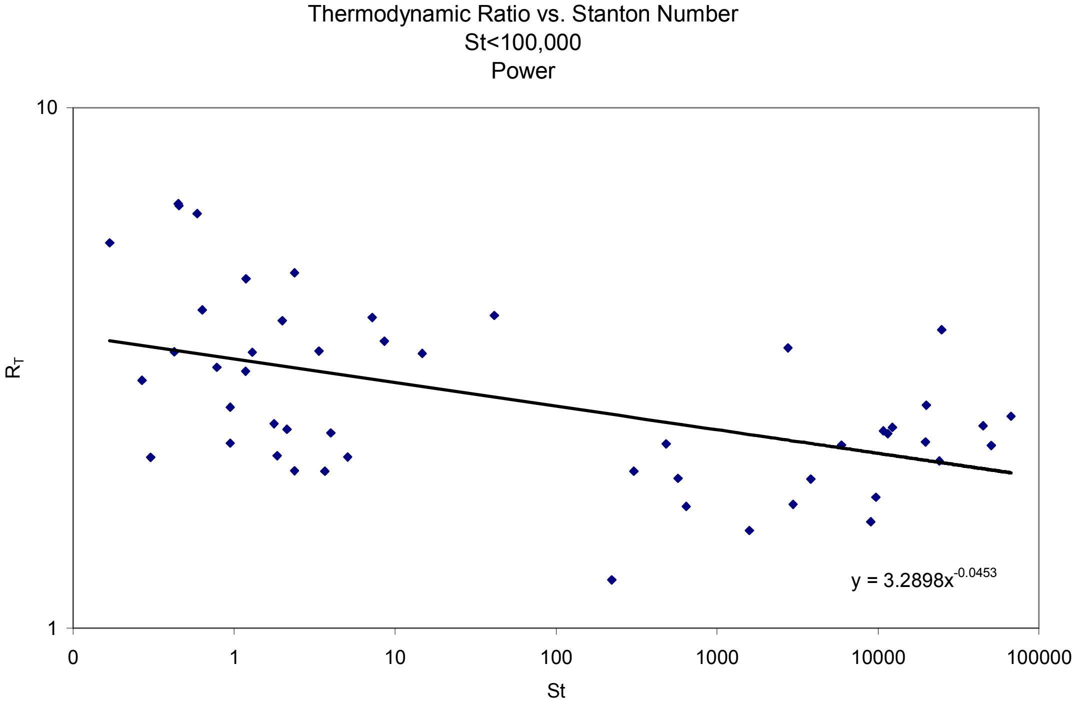

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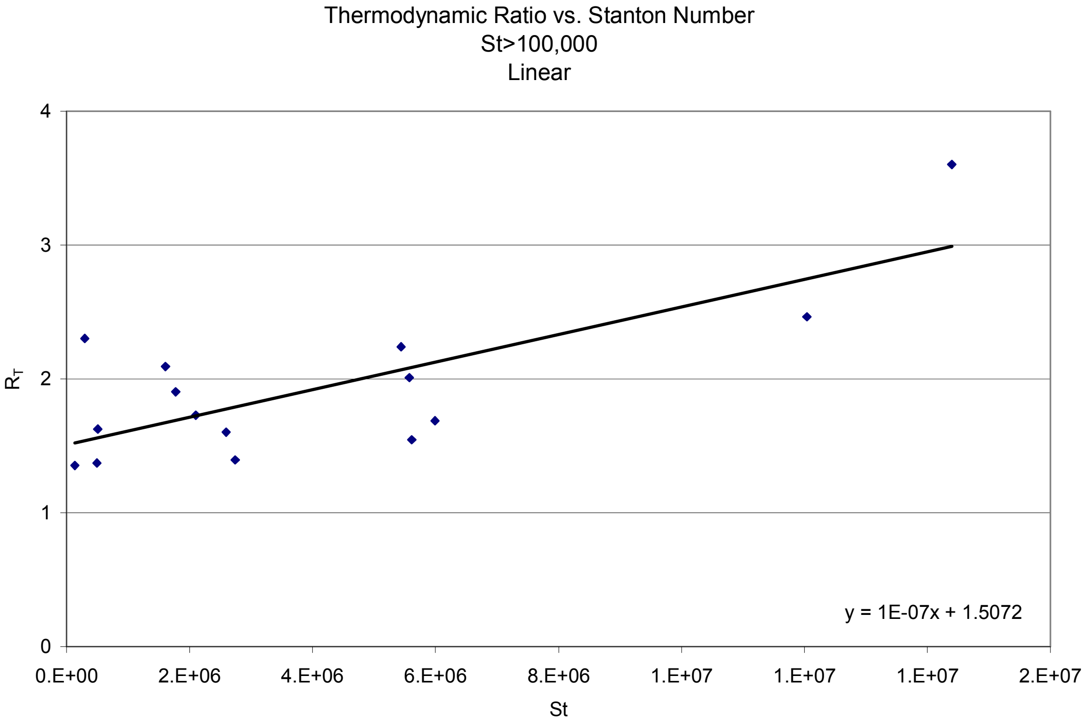

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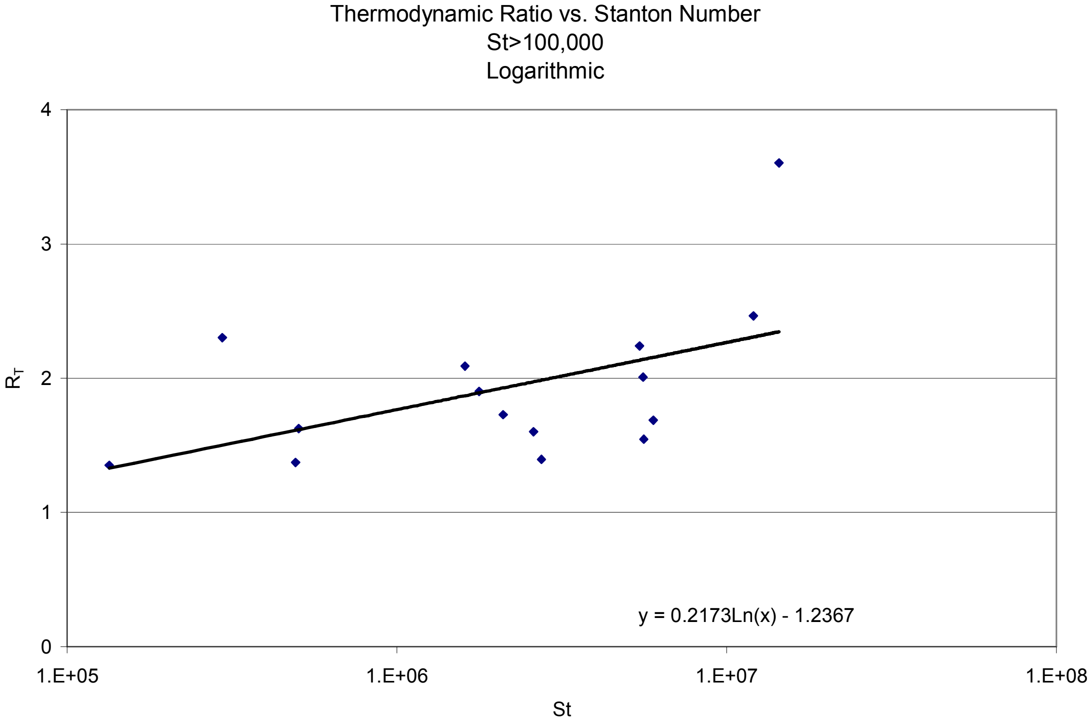

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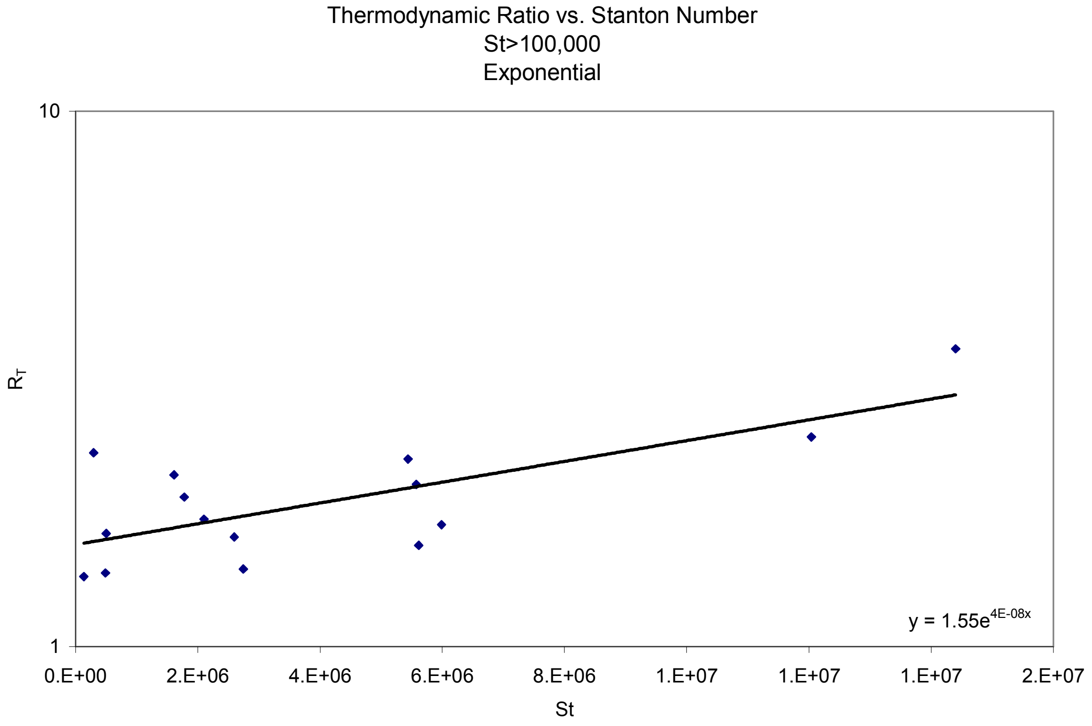

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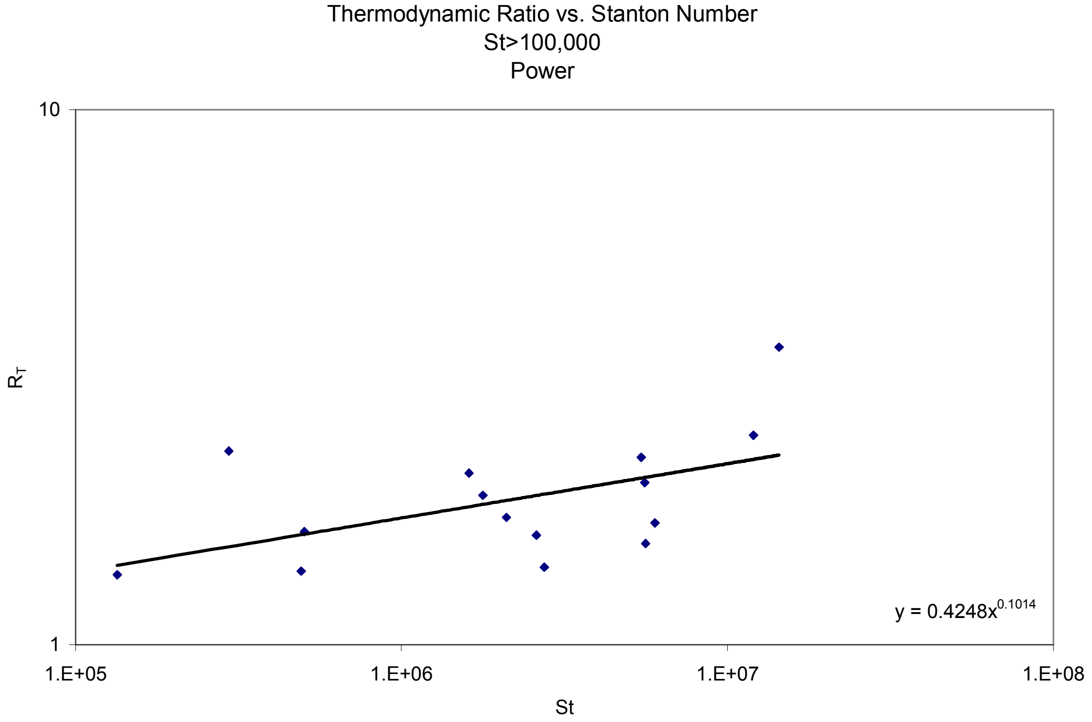

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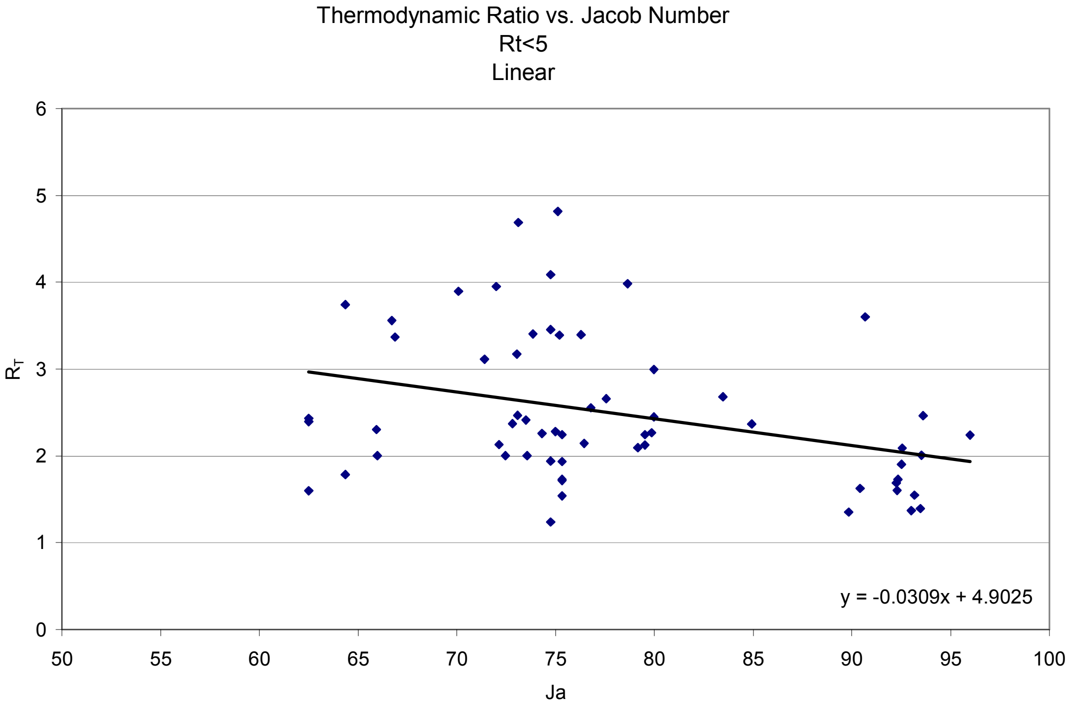

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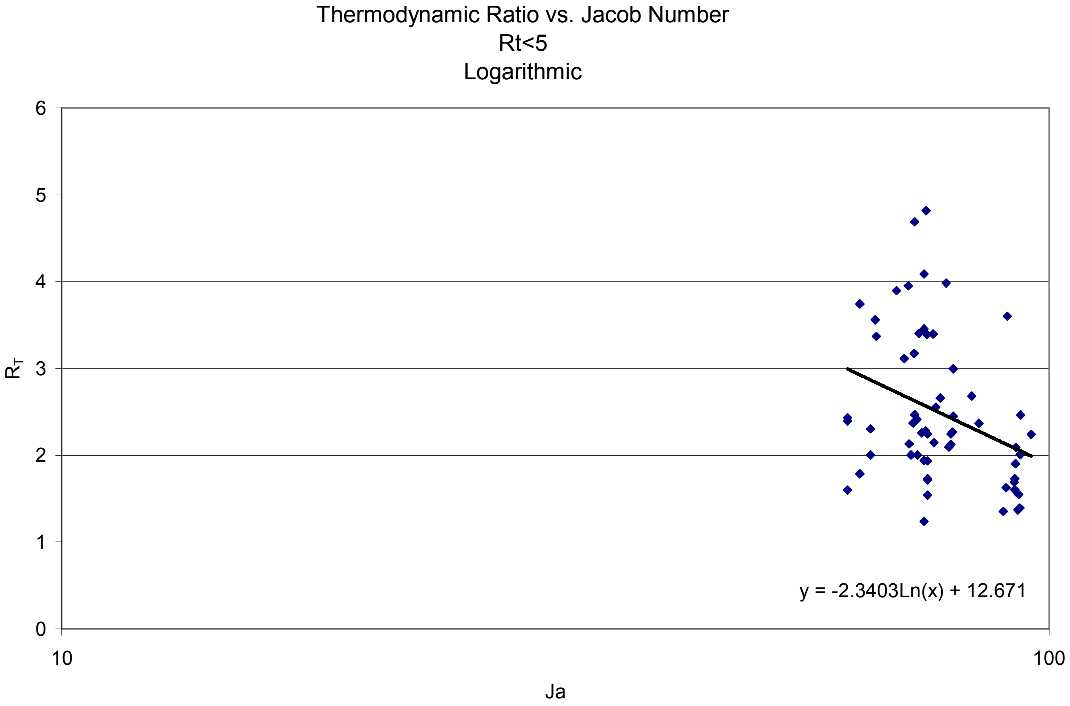

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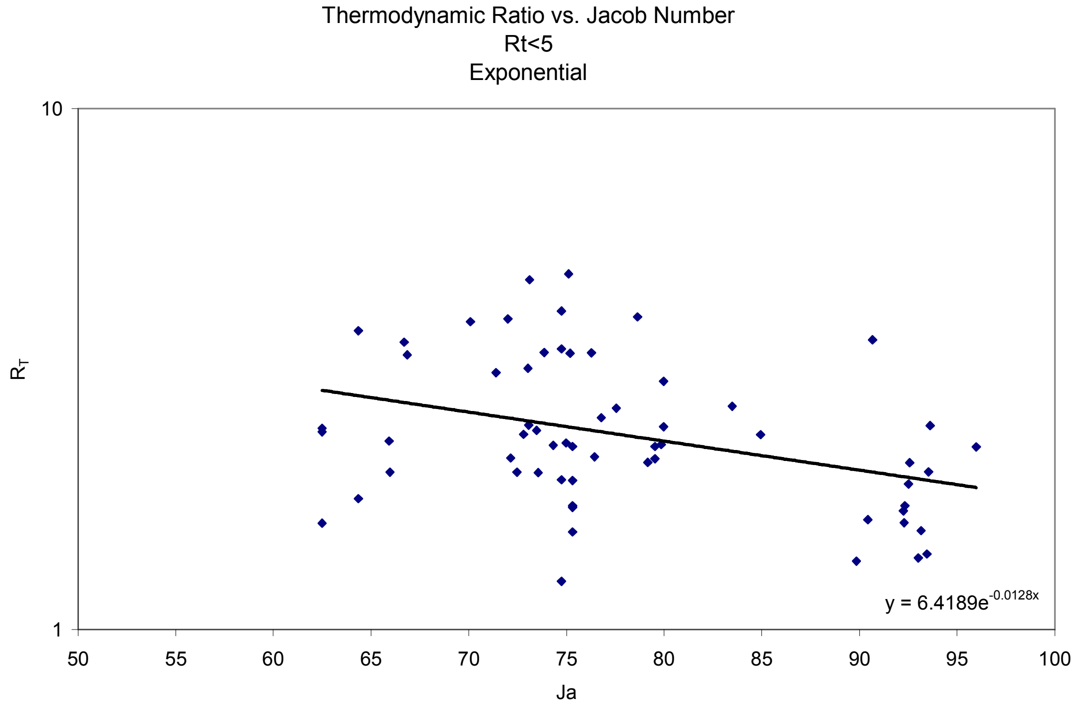

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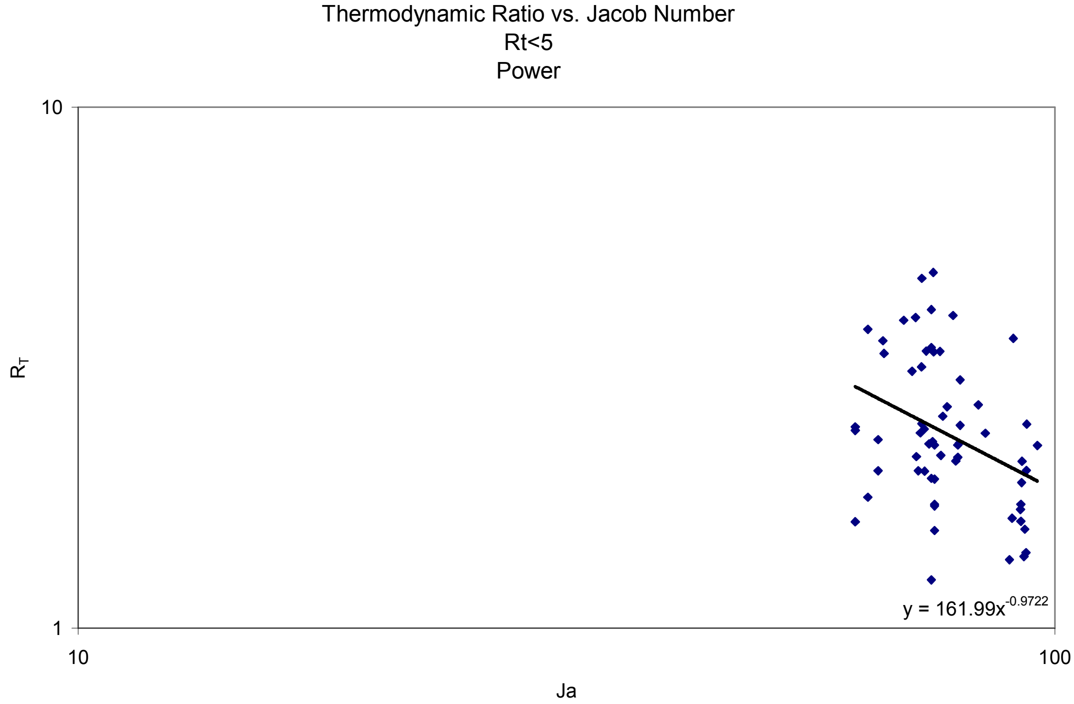

Figure H 37

VITA

Rebecca Ann Ostermann

Candidate for the Degree of

Master of Science

Thesis: DIRECT STEAM INJECTION HEATING OF LIQUID FOOD PRODUCTS

Major Field: Biosystems Engineering

Biographical:

Personal Data: Born in Colorado Springs, Colorado on May 16, 1977 the daughter of Tom and Jeanne Ostermann.

Education: Graduated from Poudre High School, Fort Collins, Colorado in April, 1995; received a Bachelor of Science degree in Biosystems Engineering from Oklahoma State University, Stillwater, Oklahoma in May, 2000. Completed the requirements for the Master of Science degree with a major in Biosystems Engineering from Oklahoma State University in December, 2005.

Professional Experience: Water Resource Engineer, CH2M Hill, Inc.
September 2004-Present

Professional Memberships: American Society of Agricultural and Biological Engineers

Name: Rebecca Ann Ostermann Date of Degree: December, 2005

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DIRECT STEAM INJECTION HEATING OF LIQUID FOOD PRODUCTS

Pages in Study: 108 Candidate for the Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study: The purpose of this research was to investigate a correlation between flow characteristics and physical properties of liquid food products and the occurrence of condensation-induced water hammer in direct steam injection heating. A linear relationship developed by Bowser et al. (2003) between the thermodynamic ratio and the Peclet number was examined for applicability to results from tests performed using water, sugar solution, beef bone stock, and corn starch. Five other dimensionless parameters were screened for potential relationships to the thermodynamic ratio that could be used to define safe operating conditions for a steam injection heater.

Findings and Conclusions: It was verified that a linear relationship between the thermodynamic ratio and the Peclet number for predicting CWH applied well to water and sugar water. Results for other food products tested in this study were inconclusive. Of the six dimensionless parameters investigated, four, the Prandlt, Reynolds, Peclet, and Stanton numbers, merited further investigation. It was also found that power and logarithmic equations may better describe a relationship to predict condensation-induced water hammer than a linear equation.

ADVISER’S APPROVAL: Dr. Timothy Bowser