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Sublimation of Naphthalene Spheres in a Natural Convection Environment

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SUBLIMATION OF NAPHTHALENE SPHERES IN A NATURAL CONVECTION ENVIRONMENT

by

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Abstract

Solid naphthalene of 99.9% purity were melted and cast into spheres using two-piece silicone molds. When cured, the spheres were removed from the molds and hung from a calibrated digital scale where data of mass loss over time was collected to obtain the sublimation rate in a natural convection environment. Data were collected until the sphere's diameter had been reduced by approximately 1% so any discrepancy in shape seen after long periods of time would not influence the results.

Data were used to find the mass transfer coefficient which was a characteristic of both the geometry and sublimating material used. Several dimensionless mass transfer parameters were calculated, including the Sherwood, Rayleigh, Grashof, and Schmidt numbers. The Schmidt number was found to have a constant value of 2.47, and the product of this number and the Grashof number resulted in a range of values for the Rayleigh number of 1.11 x 10^3 to 7.76 x 10^3. The range of Sherwood numbers calculated were 8.83 to 17.8. An empirical equation was developed from the analysis of solid naphthalene spheres of diameter 30 mm, 40 mm, 50 mm, and 58 mm. This equation relates the Sherwood number to the Rayleigh number from a linear curve fit of the data that takes the form

$$Sh = 1.32\ x\ 10^{-3} \cdot Ra + 7.37$$

and correlates the data well with an R^2 value of 0.997.

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Introduction

The naphthalene sublimation technique is an experimental method used to determine heat transfer coefficients in natural convection flows [1]. Studies have been conducted previously to determine experimental mass transfer coefficients over a range of different geometries and fluid flows by forced and natural convection. Examples include plates, cylinders in horizontal and vertical configurations, spheres, single fins and fin arrays. The goal of these experiments was to determine heat transfer coefficients by use of the mass transfer-heat transfer analogy. The two most common materials used in these experiments are naphthalene and paradichlorobenzene. They have ideal material properties in that they have relatively low melting points, are easy to cast into molds, and readily sublimate at room temperature.

Modeling of heat transfer with mass transfer is a useful tool for engineering predictions. Heat transfer coefficients are relatively difficult to obtain, usually by means of expensive and complex equipment, instruments, and measurements, whereas mass transfer experiments are simple, accurate, and inexpensive [2]. Mass transfer experiments remove the problems associated with those of heat transfer by eliminating the effects of heat leakage by radiation and conduction, and avoids uncertainties associated with possible preheating of the surrounding fluid in the boundary layer at the edges of the specimen.

Results obtained by conducting mass transfer experiments can drastically simplify investigations of heat transfer problems by means of analogous relationships. These analogous relationships are in the form of dimensionless ratios such as the Sherwood number, which describes the ratio of convective mass transfer to the rate of diffusive mass transport, which is analogous to the Nusselt number in heat transfer. It can be shown that a dimensional analysis can be performed that indicates the data of this study may also be correlated with the Grashof, Schmidt, and Rayleigh numbers [3].

The objective of this study is to produce an empirical equation to determine the mass transfer coefficient, h_m, of suspended naphthalene spheres by means of natural convection. By using different diameter spheres, the mass transfer rate acquired will be used to determine a relationship between the Sherwood and Rayleigh numbers. It is also meant to be a companion study to the research work performed by Anderson, C. [4] where paradichlorobenzene spheres were used to determine mass transfer coefficients. The same experimental methods, procedures, specimen geometries, and data analysis methods were followed closely to recreate the experimental conditions with naphthalene instead of paradichlorobenzene.

Literature Review

The literature review will consist primarily of recently published works that involve natural convection with various geometries, using naphthalene and paradichlorobenzene. In recent years, experiments have been performed using both paradichlorobenzene and naphthalene to determine the sublimation rates for a variety of geometries. Anderson, C. [4] cast spherical paradichlorobenzene specimens of diameter 30 mm, 40 mm, 50 mm, and 58 mm and of 99.9% purity in silicone molds then allowed them to sublimate in a natural convection environment. For each size sphere, mass loss over time was recorded by suspending the test pieces under a calibrated digital scale by a weigh-below hook. The scale was connected to a laptop PC and data was transmitted by means of a spreadsheet set to record measurements every five minutes until a 1% reduction in diameter was realized. Three trials of each size were performed. When the data were plotted, a best-fit linear curve was generated to find the sublimation rate. These results were used to find the Sherwood, Rayleigh, Schmidt, and Grashof numbers and an empirical equation was developed to correlate the Sherwood number as a function of the Rayleigh number. The Sherwood number was found in the range of 17.3 to 24.9 and the range of Rayleigh numbers were from 42.6 x 10^3 to 2.98 x 10^5. The spheres were left to sublimate for up to four weeks past the time when last data point was taken. After several days, the specimens' shape became distorted and pits began to form on the surface.

In another study, Anderson, W. [5] tested 99.8% pure paradichlorobenzene spheres of diameter 40.3 mm, 67.7 mm, and 84.6 mm that were cast using rubber ball molds. A wooden skewer was secured in the mold before the molten paradichlorobenzene was poured, then subsequently capped off with a paraffin wax plug. The rubber mold was such that no lubrication or releasing agent was required to remove the casting from the mold. The spheres were given 12 hours minimum to cure before topping off the material to account for any losses and removed. The elapsed time between the removal of the casting from the mold and the time they were hung from the scale by a weigh-below hook was considered small enough to disregard any losses due to sublimation. LabX direct balance software was used as the medium to collect data from a Mettler Toledo MS model scale where data was recorded every 60 seconds until there was a reduction in diameter of 0.5%. To ensure the paradichlorobenzene vapor was completely dissipated from the room, two to three days were allowed between sample runs. The data were plotted to find the mass transfer rate by best-fit linear curve and a second order empirical equation was found to relate the Sherwood number as a function of the Rayleigh number. It was noted that a slight "feathering" developed as a ring around the top of the spheres and the shape became distorted only after they continued to sublimate well past the end of testing.

Cylinders are another type of geometry used to find mass transfer rates of sublimating materials in either a vertical or horizontal configuration. Carley [2] used the naphthalene sublimation technique to determine mass transfer rates of vertically oriented naphthalene cylinders in a natural convection environment. Three solid cylinders which measured one, one and a half, and two-inch nominal diameter and 10-inch nominal overall length were cast using aluminum molds. The molds were cleaned with rubbing alcohol and coated with Pam cooking spray before the two halves were bolted together and molten naphthalene was poured. The experiments were terminated after a diameter reduction of 0.100 in. was measured so that any distortion of shape did not influence the data collected. Correlations were made between the Sherwood and Rayleigh numbers, Sherwood and Grashof numbers, and the mass transfer rate and cylinder diameter. The cylinders, being in a vertical orientation, caused the shape deformation to occur in a top down fashion, as the heavier vapor density of the naphthalene compared with the surrounding air caused the vapor to travel down the length of the cylinder. This had an overall effect on the local sublimation rates relative to the location on the cylinder surface where the less saturated boundary layer at the top of the cylinder experienced a higher mass loss than the bottom.

Bautista [3] studied the sublimation rates of solid 99.8% pure paradichlorobenzene cylinders suspended horizontally in a natural convection environment. The cylinders were cast in aluminum molds and consisted of one, one and a half, and two-inch nominal diameter with a nominal length of 10 inches. A study of the volumetric contraction of paradichlorobenzene was carried out in graduated beakers, comparing the total reduction in volume of the material while exposed to air and when sealed from the environment over a period of one hour. The results showed they compared favorably. Sublimation rates were determined by collecting data on mass loss over time and a linear correlation was determined between the Sherwood and Rayleigh numbers. The range of Sherwood numbers were 4.7 to 21 and the range of Rayleigh numbers was 1.42×10^4 to 1.13×10^5.

Rectangular naphthalene plates were tested using forced convection to obtain mass transfer coefficients to simulate the cooling effects of electronic modules mounted in various locations on printed circuit boards by Schmidt [6]. The 12 mm x 10.8 mm plate was cast by a mold made of hardened steel and polished to a mirror-like finish which allowed the naphthalene specimen to be removed from the mold relatively easy. A pre-run was performed in the test section prior to data collection to ensure the plate was at a uniform temperature with the surroundings and any loose pieces of naphthalene were removed from the surface. The specimen was then removed, weighed, then placed back in the test section for 20-30 minutes to perform the data run. A correction was applied to the difference of the before and after-run measurements to account for losses due to natural convection during the time spent performing weight and size measurements. The Sherwood number was calculated from the results, and using the heat-mass transfer analogy, a value was obtained for the Nusselt number and then the heat transfer coefficient was determined.

Gaps in current literature show a need for more studies involving spherical geometry. What has been presented here has shown that six different diameters of spheres have been tested using paradichlorobenzene as the sublimating material in a natural convection environment. The results of this study will used to continue research in this field by complementing the Anderson, C. [4] study by use of naphthalene in place of paradichlorobenzene. Other past spherical studies in both heat and mass transfer include heat transfer by forced convection of ice spheres in water [7], and mass transfer by forced convection of benzoic acid spheres in water [8].

Procedure

In order to create spherical specimens of naphthalene, molds were created. It was determined that silicone would be a sufficient material. A solution was found in which 3D printed materials could be combined with silicone to produce the desired molds. Anderson, C. [4] designed and printed mold negatives in which liquid silicone could then be poured and allowed to cure. The mold negatives were printed using ABS and vapor smoothed to ensure no texture or layer lines remained on the mold surfaces. The silicone was mixed and poured into the negatives and allowed to cure. The resulting molds were thick with just the right amount of rigidity to give the support and consistency needed to produce accurate molds that could be used repeatedly to make the spherical specimens. An example of one of the molds used is shown below in Figure 1.

Figure 1: *Two-piece molds used for casting naphthalene (middle) and mold negatives (top and bottom) used for the construction and curing of the two mold halves [4]. Reprinted with permission.*

Casting Specimens

Naphthalene of 99.9% purity was cast into spherical specimens by melting the material in a small stainless-steel pan atop a hot plate and pouring it into the molds after the molds were thoroughly cleaned with isopropyl alcohol. After some experimentation, a method was developed to ensure the best possible castings were used for the experiment. With a boiling point of approximately 80 °C, care was taken not to get the liquid much hotter than this temperature for two reasons: to keep curing time at a minimum and to reduce the temperature difference between material and mold. One issue noted was the effect of the material flash cooling on the surface of the mold directly after pouring. Flash cooling is a problem in that the surface of the sphere would end up textured, cracked, and/or produced uneven surfaces. The hotter the material was, and hence the larger the temperature difference was, the more imperfections showed up in the end product. Keeping the material just above melting point was accomplished by using a handheld laser thermometer. The naphthalene was poured into the molds at temperatures between 82-85 °C which proved to be just enough to hold the material at a liquid state long enough to fill the mold. It also assured that vapor losses due to excessive heat were kept to a minimum. To lessen the temperature difference, the inner mold surfaces were preheated with a hand-held heat gun. This allowed the liquid naphthalene to cool slowly and evenly.

A fishing line was routed through the top of the mold with a sewing needle before pouring as a means to hang the specimen under the scale. The silicone, being as flexible as it was, allowed the small hole it produced to close around the fishing line and not influence the resulting cast specimen. The end of the fishing line left inside the mold was slightly melted with a lighter to create a knot, assuring the line would not be pulled out of the sphere during transport and suspension. The other end was tied in a knot with a loop on the end after the specimen was removed from the mold to hang on the scale support apparatus in which the specimen was hung.

After melting the naphthalene, preparing the fishing line, and preheating the mold surfaces, the liquid material was poured into the mold and allowed to cool and solidify. To speed up the process, after 10-15 minutes exposed to room temperature, the mold was moved into a small refrigerator using an aluminum plate to sit upon so the mold would not flex and distort the spherical shape after being picked up. The mold was then left to cool in the refrigerator for 30-60 minutes depending on the specimen size. As liquid naphthalene cools and solidifies, its density increases resulting from a decrease in volume per a constant mass. This was verifiable after each mold was removed from the refrigerator. To combat this, the mold cavity was topped off with more liquid naphthalene and was then allowed to cool in room temperature until fully cured, between 1-2 hours depending on size. An 8 mm hole in the top of the mold where the liquid was poured in allowed a cylindrical “plug” to exist on the top of the sphere that allowed the material to contract without affecting the sphere itself. This plug was trimmed away carefully after removing the specimen from the mold to preserve the intended spherical shape.

Once cured, the mold halves were separated, exposing the specimen inside. The surface was inspected for imperfections at this time. Six diameter measurements were taken from the sphere with digital calipers in different locations to ensure the casting retained its spherical shape and nominal dimensions. These reported diameter results, shown in Table 2, are within ±0.02 mm to the true value. The temperature of the room was also recorded. The hanging apparatus was checked for proper balance on the scale and the readout was tared to account for its weight. Once verified, a loop was tied on the end of the fishing line and the specimen was hung from the scale and the spreadsheet was prompted to start receiving data. The scale set up, with specimen attached, is shown below in Figure 2.

Figure 2: *Scale and weigh-below hook apparatus with suspended specimen for testing [4]. Reprinted with permission.*

Data Acquisition

The data required for this experiment included spherical diameter, temperature, and mass loss over time. Data were acquired using a calibrated Mettler Toledo PB 153-S digital scale elevated on a stand in which a hanging apparatus was fabricated that allowed the spherical specimen to hang underneath. The scale is precise to a milligram with a maximum capacity of 151 ±0.001 g. A laptop was connected to the scale by means of an RS232C data cable for communication. A spreadsheet was used to ping the scale every five minutes and store the data received. A table was automatically generated in a spreadsheet to include the mass reading from the scale in grams and the actual time at which that value was recorded. This was made possible through a macro program written with visual basic code.

The scale, specimen, and laptop were placed inside a 42,000 cubic foot [4] well ventilated laboratory environment. Timing was such that there was very little, if any, foot traffic throughout the lab as normally this laboratory is full of students and faculty coming and going, opening and closing doors, etc. The objective was to maintain as stable an atmosphere as possible during testing. Due to the size of the laboratory relative to the specimen size and the ventilation of the room meant that the room would not get saturated with naphthalene vapor and a steady flow of fresh air was consistently replenished. If not for this, the buildup of naphthalene vapor would have slowed the rate of sublimation and possibly rendered the trials inconclusive, if the saturation of the naphthalene vapor in the surrounding atmosphere was unaccounted for.

One of the goals of the experiment trials was to collect mass and time data until the diameter of the sphere was reduced by approximately 1%. Each trial was performed over 24-48 hours depending on sphere size. The experiments were terminated once the desired size limit was reached. This assured the sphere's geometry remained true to shape. After the required testing period had elapsed, the specimen was moved into an adjacent room where it continued to sublimate. No additional data were collected during this time, but diameter measurements continued, and only the shape of the specimen was monitored. It was found for most specimens that an additional 24-48 hours were all that was needed for the spheres to start to become either elongated, egg-shaped, or otherwise distorted from its original form. It was assumed that any data collected after this time would be unreliable as local sublimation rates would begin to vary at a given locations on the sphere.

Overall, six trials were completed on four different size spheres: 30 mm, 40 mm, 50 mm, and 58 mm. Ideally, one trial would be performed for each size but there were issues found with two trials. The first 30 mm trial after testing was found to have developed a hole on the top of the sphere where the casting plug was initially removed. It was concluded that an air pocket was trapped underneath the surface as the material was topped off in the mold and became exposed during testing, so another trial for that size sphere was performed. The second trial was recorded in the results, but a comparison of the two trials was performed and it was found that there was less than a 1% difference in the mass transfer rates between the results of the two trials. The data of this trial are shown in Figure 9 in the Appendix for reference.

The second trial affected was the first 58 mm sphere tested. When the data were analyzed directly after testing, a substantial fluctuation in the mass loss over time was observed from the graph. After constructing a trendline of the data, it showed a significant oscillation around the trendline where the mass loss was increasing and decreasing in a consistent pattern over most of the duration of the test. The data of this trial were plotted and shown in Figure 10 in the Appendix for reference. It was later found that an employee was in and out of the lab for most of the weekend when testing was performed. Two opposing doors of the lab were propped open and a large bay door was opened and closed numerous times throughout the day. Another trial of that size sphere was performed and included in the results.

Equations

The naphthalene sublimation technique is used to determine heat transfer coefficients in convection flows by performing mass transfer experiments in the lab and converting these results by the heat transfer-mass transfer analogy. The driving force for heat diffusion is proportional to a temperature difference with its intensity decided by the thermal conductivity of the acting medium according to Fourier's Law. Likewise, for mass transfer, the driving force is proportional to a concentration difference resulting in a density gradient in a two-component mixture and the mass diffusivity of one component into the other according to Fick's Law:

$$N_A = -D_{AB} \frac{\partial C_A}{\partial r}\bigg|_{r=0} \tag{1}$$

where N_A is the amount of naphthalene per unit time per unit area, D_{AB} is the mass diffusivity found experimentally by Sogin [9] and used here, and $\partial C_A/\partial r$ is the concentration gradient at the surface of the sphere.

The molar flux equation for mass transfer is analogous to Newton's Law of Cooling in heat transfer:

$$N_A = h_m(C_{A-}C_\infty) \tag{2}$$

where h_m is the mass transfer coefficient, C_A is the concentration of naphthalene at the surface of the sphere, and C_∞ is the concentration of naphthalene in the surrounding environment. Substituting $\dot{m}/A_s$ for N_A and solving results in an equation for the mass transfer coefficient:

$$h_m = \frac{\dot{m}}{A_S(\rho_{v,s} - \rho_{v,\infty})} \tag{3}$$

where $\dot{m}$ is the mass loss per unit time of sublimating naphthalene recorded in the experiment, A_S is the surface area of the sphere, $\rho_{v,s}$ is the vapor density of naphthalene at the surface, and $\rho_{v,\infty}$ is the vapor density of naphthalene in the surrounding environment. The vapor density very far from the surface of the sphere (r → ∞) is assumed to be negligible due to the laboratory room being adequately ventilated and having a volume of approximately 42,000 cubic feet.

Since the partial pressure of naphthalene is always very low compared to atmospheric conditions, the ideal gas law can be used to find the vapor density of naphthalene at the surface [1]:

$$\rho_{v,s} = \frac{p_{v,s}}{R_v T_s} \tag{4}$$

where $p_{v,s}$ is the vapor pressure of naphthalene at the surface of the sphere, R_v is the gas constant of naphthalene vapor whose magnitude was the value reported by Sogin [9], and T_s is the surface temperature of the naphthalene sphere. An empirical equation for the partial pressure of naphthalene was developed also by Sogin [9]:

$$p_{v,s} = 10^{\left(B_1 - \frac{B_2}{T_s}\right)} \tag{5}$$

where B_1 and B_2 are material constants and for naphthalene take the values of 11.884 and 6713 respectively. Substituting the constants and the sphere surface temperature, T_s in degrees Rankine give the vapor pressure of naphthalene vapor in psf. This value can be easily converted to Pa by multiplying equation 5 by 47.88 [3].

With the data collected in the experiment and performing the calculations above, it is now possible to determine the sought-after values for the relevant dimensionless parameters to complete the mass transfer analysis. These parameters, as stated above are the Sherwood number, Grashof number, Schmidt number, and Rayleigh number. The Sherwood number, whose counterpart in heat transfer is the Nusselt number, is the ratio of convective mass transfer to the rate of mass diffusion:

$$Sh = \frac{h_m D}{D_{AB}} \tag{6}$$

where h_m is the mass transfer coefficient, D is the sphere diameter, and D_{AB} is the diffusion coefficient. The Grashof number is the ratio of buoyancy to viscous forces acting on a fluid:

$$Gr = \frac{\rho_{air} D^3 g (\rho_{v,s} - \rho_{v,\infty})}{\mu_{air}^2} \tag{7}$$

where ρ_{air} is the density of air, D is the sphere diameter, g is the gravitational constant, $\rho_{v,s}$ is the vapor density of naphthalene at the surface of the sphere, $\rho_{v,\infty}$ is the vapor density of naphthalene in the surrounding environment, and μ_{air} is the absolute viscosity of air. The Schmidt number, whose counterpart in heat transfer is the Prandtl number, is the ratio of momentum and mass diffusivities: the kinematic viscosity of air to the mass diffusion rate:

$$Sc = \frac{\nu_{air}}{D_{AB}} \tag{8}$$

where ν_{air} is the kinematic viscosity of air. This value is treated as a constant, whose value is shown in Table 1. The Rayleigh number is the product of the Grashof and Schmidt numbers and is the ratio of buoyancy and viscous forces and momentum and mass diffusivities:

$$Ra = Gr \cdot Sc = \frac{\rho_{air} D^3 g(\rho_{v,s}\rho_{v,\infty})}{\mu_{air}^2} \cdot \frac{\nu_{air}}{D_{AB}} \tag{9}$$

There are several assumptions necessary for this study and are described below:

- For natural convection, the mass transfer process is adiabatic, as any heat transfer in the boundary layer would affect the sublimation rate and analogy between them is lost.
- Fluid properties are constant, and naphthalene vapor behaves as an ideal gas.
- There is an isothermal relationship in the boundary between the naphthalene specimen and the surrounding environment.
- The density of naphthalene vapor at a significant distance from the testing site in the laboratory is zero.
- No chemical reactions take place.
- Humidity has a negligible effect in the experiment.
- Equimolar counter diffusion takes place, i.e. $D_{AB} = -D_{BA}$

Results

The constants used for all calculations are listed in Table 1. The sublimation rate for each sized sphere was determined by experiment and comes from data collected of mass loss over time and plotted in a spreadsheet with time as the independent variable and mass as the dependent variable. The mass transfer rates were determined with a linear curve fit. When compared it was noted that the data collected was not perfectly linear as there were slight fluctuations in the mass loss, which was attributed to slight variations in air flow in the lab. It was assumed these minor fluctuations did not affect the results. This can be seen in the plots, in Figures 4-7. Data for each sized sphere is shown in Table 2.

Table 1: *Constants used for reduced data.*

Ambient Temperature, T_w (°C)	22.2
Ideal Gas Constant, R_v (J/kg·K) [9]	64.87
Partial Pressure of Naphthalene, p_v (Pa)	8.667
Vapor Density of Naphthalene, ρ_v (kg/m^3)	4.524×10^{-4}
Diffusion Coefficient, D_{AB} (m^2/s) [9]	6.116×10^{-6}
Kinematic Viscosity, υ_{air} (m^2/s) [11]	1.511×10^{-5}
Absolute Viscosity, μ_{air} (N·s/m^2) [11]	1.812×10^{-5}
Density of Air, ρ_{air} (kg/m^3) [11]	1.199
Schmidt Number, Sc	2.47
Gravitational Constant, g (m/s^2)	9.81

Table 2: *Reduced experimental data*

Nominal Diameter (mm)	Measured Diameter (mm)	A_s (m^2)	$\dot{m}$ (kg/s)	h_m (m/s)	Sh	Gr	Ra
30	30.24	0.00287	2.32E-09	0.00178	8.83	448	1108
40	39.98	0.00499	3.77E-09	0.00167	10.9	1028	2540
50	49.63	0.00774	5.83E-09	0.00166	13.5	1982	4897
58	57.87	0.01052	8.95E-09	0.00188	17.8	3141	7761

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The experiments were run until a reduction in diameter had reached approximately 1%. This was so the specimens remained spherical and the change in shape that was observed over the days following the experiments did not influence the results. Once the data was analyzed and plotted, a resulting correlation could be found relating the Sherwood number to Rayleigh number. The Grashof number was not solely used for the mass transfer correlation to minimize the separate dependence of the Sherwood number on the Schmidt number [10]. The results are shown below in Figure 3. The results yielded the following empirical equation relating the Sherwood number to the Rayleigh number:

$$Sh = 1.32\ x\ 10^{-3} \cdot Ra + 7.37 \tag{10}$$

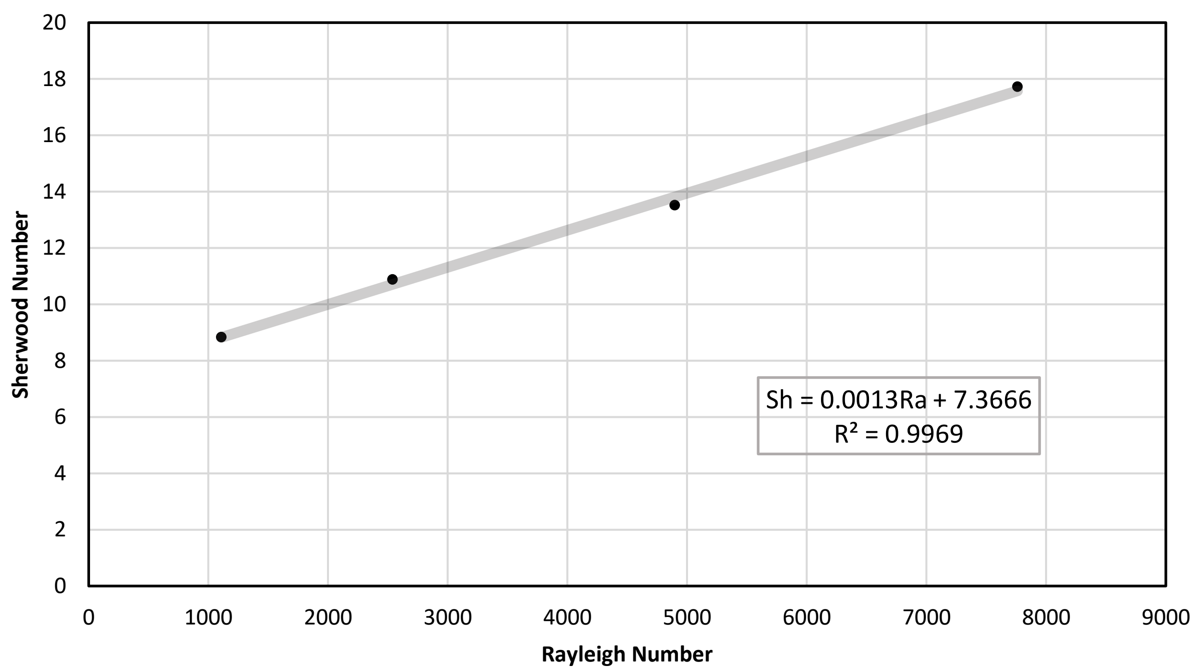

Figure 3: *Sherwood number as a function of the Rayleigh number for naphthalene spheres of diameter 30 mm, 40 mm, 50 mm, and 58 mm.*

The results above show that there is a linear correlation between the Sherwood and Rayleigh numbers for sublimating naphthalene of a spherical geometry in a natural convection environment. This final relationship is shown in Equation (10), taken from the best fit line of Figure 3. The square of the correlation coefficient for this set of data is 0.997.

These results are plotted with the Anderson [4] results for comparison, and are included in the Appendix, Figures 11-15. Figure 11 shows the Sherwood and Rayleigh number relation for all naphthalene and paradichlorobenzene spheres tested in both studies. Figures 12-15 contain the raw data collected and represents the mass transfer rates of naphthalene and paradichlorobenzene spheres for their respective diameters.

The results of this study allow an investigation into published heat transfer results using the mass/heat transfer analogy since, mathematically, the similarities between the two are sufficiently similar.

Discussion and Conclusion

Spheres were cast using store bought 99.9% pure naphthalene. They were melted to liquid form using a small stainless-steel pan heated on a hot plate and poured into silicone-based molds and allowed to cool and harden into spheres. The spheres were then suspended from the scale and connected to a laptop through a RS232 data cable where a Microsoft Excel Macro Spreadsheet would ping the scale every five minutes and receive the weight of the specimen at that time. Data for mass loss over time was collected until the diameter of the sphere had reduced by approximately 1% of the original averaged value.

Each specimen was moved to a different room, then allowed to sublimate for additional time after the initial data was recorded to observe how they would change over time, typically one to two weeks. Observations due to diameter and shape changes and surface imperfections were noted. In just a few days' time, the spheres would become elongated, then appear egg or pear shaped, but the surfaces remained very smooth with a glass-like appearance. Pits and voids formed in certain areas on the surface due to trapped air bubbles.

Sources of error in this experiment include minute variations in the diameter of the spheres due to the flexibility of the molds resulting in a slightly out-of-round condition, therefore several measurements were taken, and an average diameter was then used to perform calculations. Trapped air pockets may have found their way to the surface of the spheres during testing, even though a thorough visual inspection was performed periodically during testing and at its conclusion. There was a single known instance where this was the case, with the first 30 mm diameter sphere, and a new sphere was re-cast and testing re-run. However, there was less than a 1% difference in the mass transfer rate between the two trial runs. Even still, data collected for that sphere was not included in the results. These trapped air pockets also affected the overall mass of each casting, and it was determined that these were a product of the casting process, forming as the naphthalene contracted and cooled. Any voids that would have showed itself would have changed the surface area of the specimen at any given time, causing additional unseen error in the calculated mass transfer coefficient.

Air drafts and pressure changes were an unfortunate side effect of performing the experiments in a well-ventilated laboratory. This caused slight variations in the mass loss during testing and can be seen in the graphs, Figures 4-7. Data were collected in December, so there were certainly small instabilities in temperature as well, due to HVAC operations and opening and closing of doors, as one of the walls that contained an entry/exit door was adjacent to a parking lot.

Relative uncertainties were calculated based on the methods outlined by Moffat [12] and are shown below in Table 3.

Table 3: Percent uncertainty of raw and reduced data of this study.

Nominal Diameter (mm)	Measured Diameter	A_s	$\dot{m}$	h_m	Sh	Gr	Ra
30	±0.07	±1.32	±0.006	±0.60	±6.10	±0.20	±0.08
40	±0.05	±0.38	±0.003	±0.30	±5.20	±0.15	±0.06
50	±0.04	±0.48	±0.002	±0.11	±2.92	±0.12	±0.05
58	±0.04	±0.57	±0.001	±0.07	±2.53	±0.10	±0.04

Recommendations for Future Work

A comparison of this work and of Anderson, C. [4] can be carried out to identify any sources of error and/or provide information on areas of improvement. The method used in both studies can be applied to different sublimating materials, different sized spheres, or different cast geometries to see how they compare. The spherical sizes used in this study were based on the sizes produced and tested by Anderson, C. [4] and were limited by the weighing capacity of the scale. Forced convection studies can also be carried out for the specimens' sizes used here. The results of this study can be used further to apply the analogy of heat and mass transfer, and results compared with existing heat transfer correlations.

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Appendix

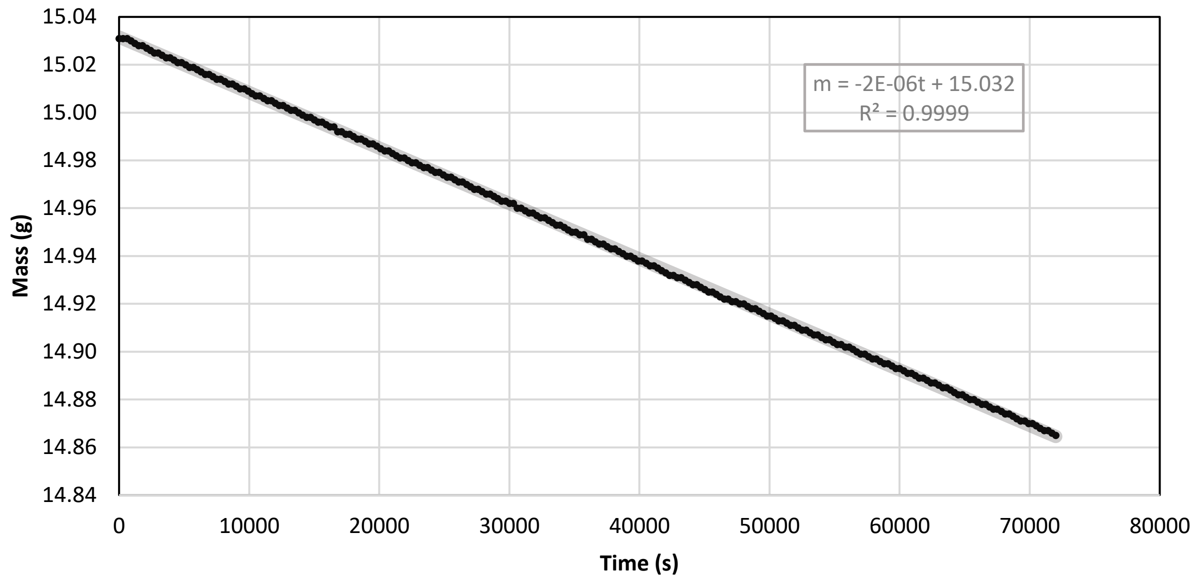

Figure 4: *Raw experimental data for the 30 mm naphthalene sphere.*

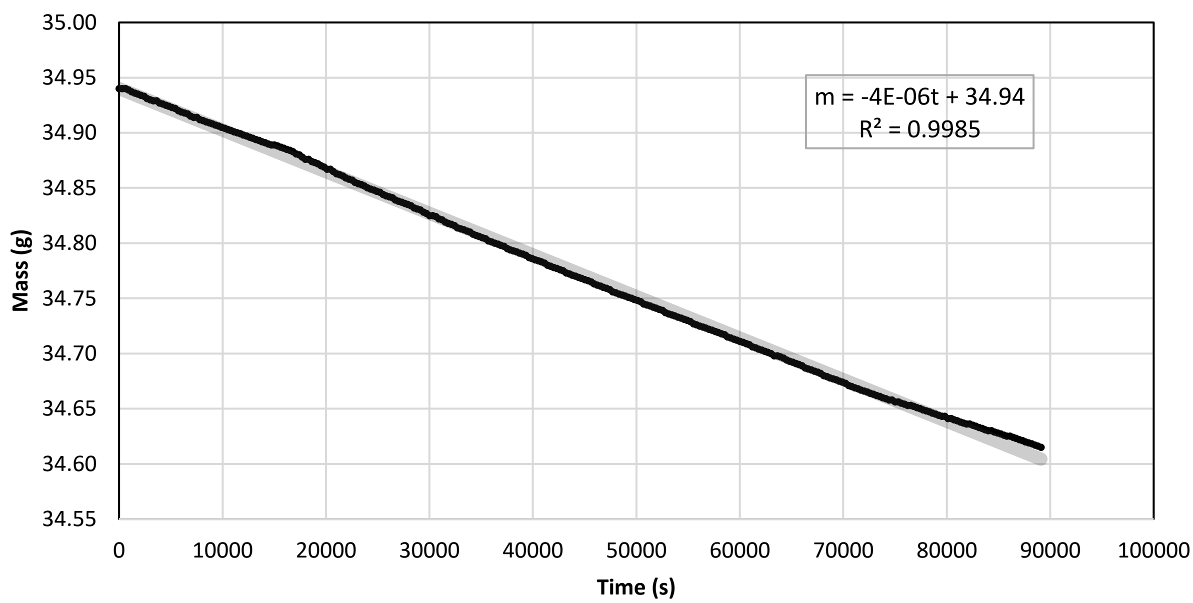

Figure 5: *Raw experimental data for the 40 mm naphthalene sphere.*

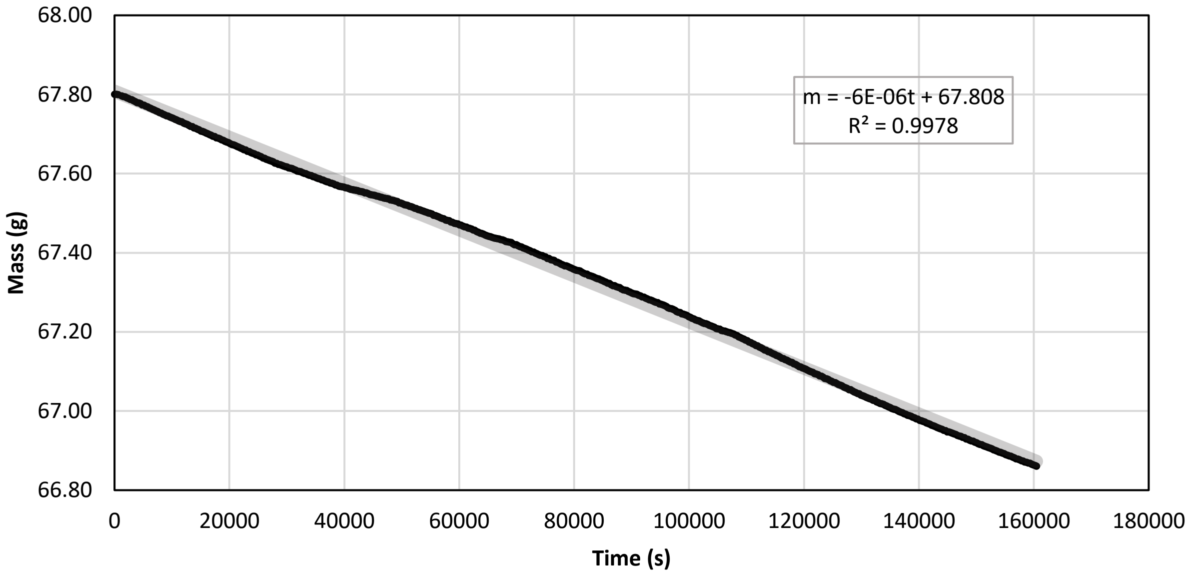

Figure 6: *Raw experimental data for the 50 mm naphthalene sphere.*

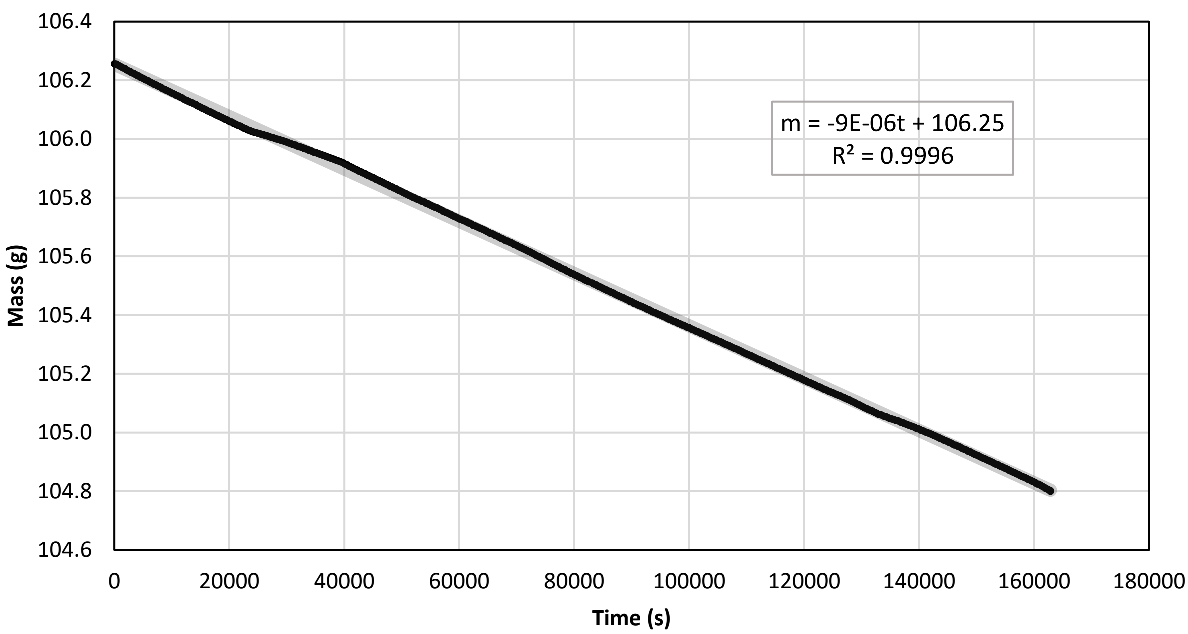

Figure 7: *Raw experimental data for the 58 mm naphthalene sphere.*

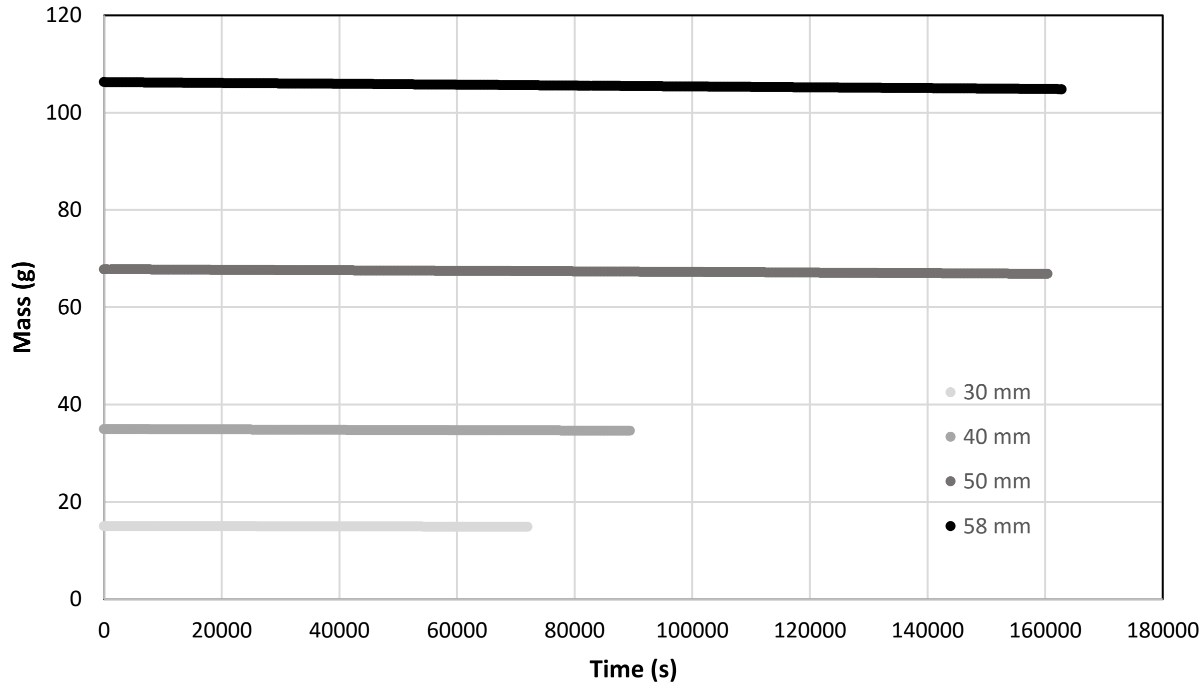

Figure 8: *Comparison of mass transfer rates for all spheres in this study*

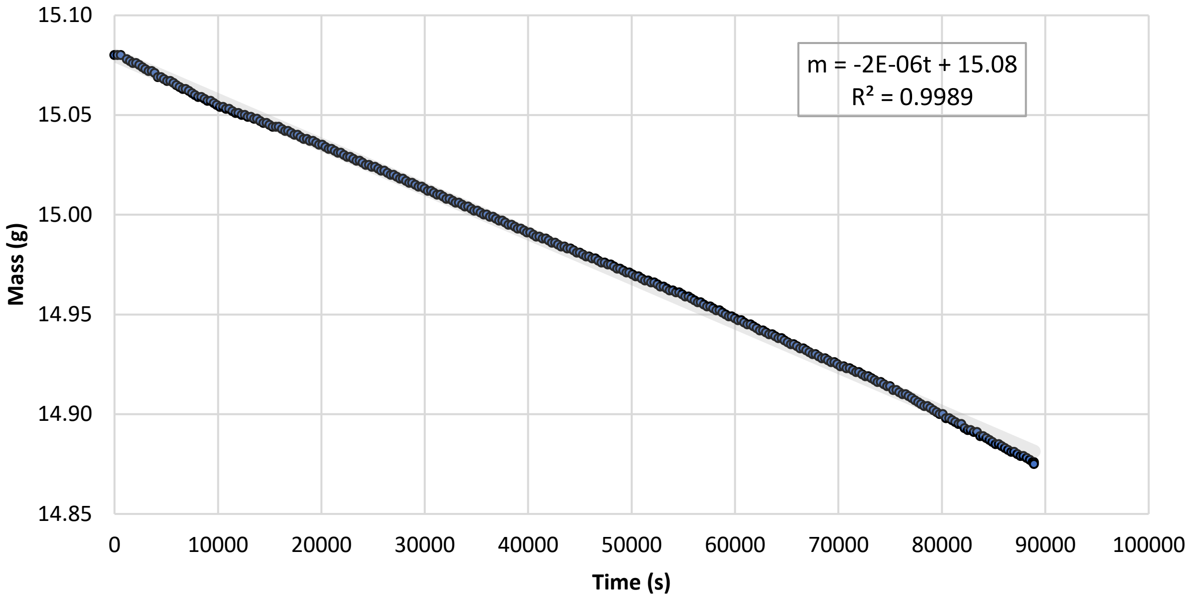

Figure 9: *Raw experimental data for the first run of the 30 mm sphere. This data was not included in the results as a large pit opened on the surface due to an exposed air pocket. Figure shown for reference only.*

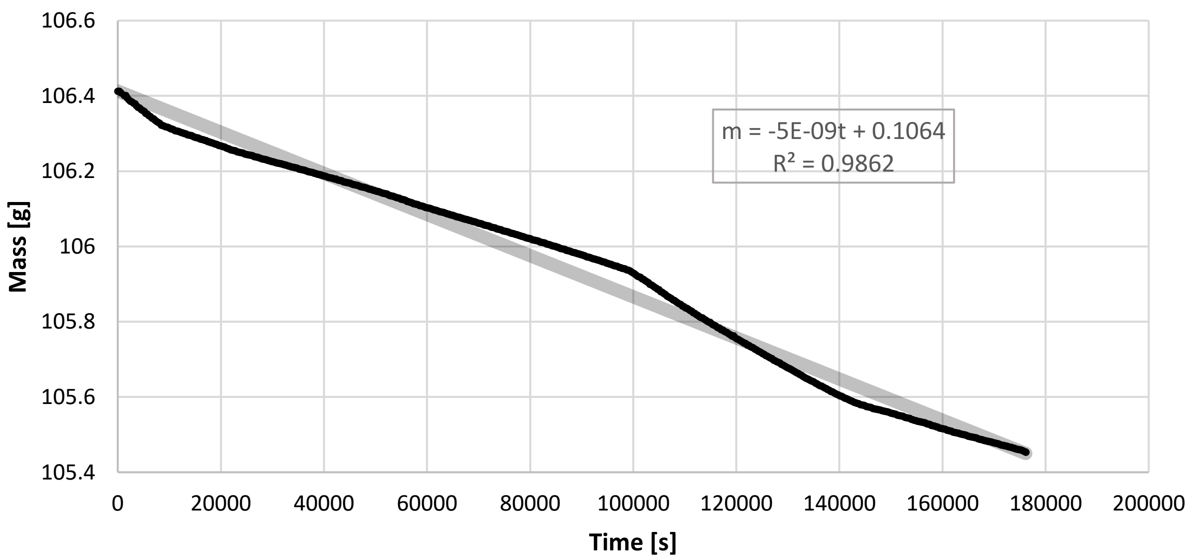

Figure 10: *Raw experimental data for the first run of the 58 mm sphere. This data was not included in the results as it was found an employee was in and out of the lab during testing. Figure shown for reference only.*

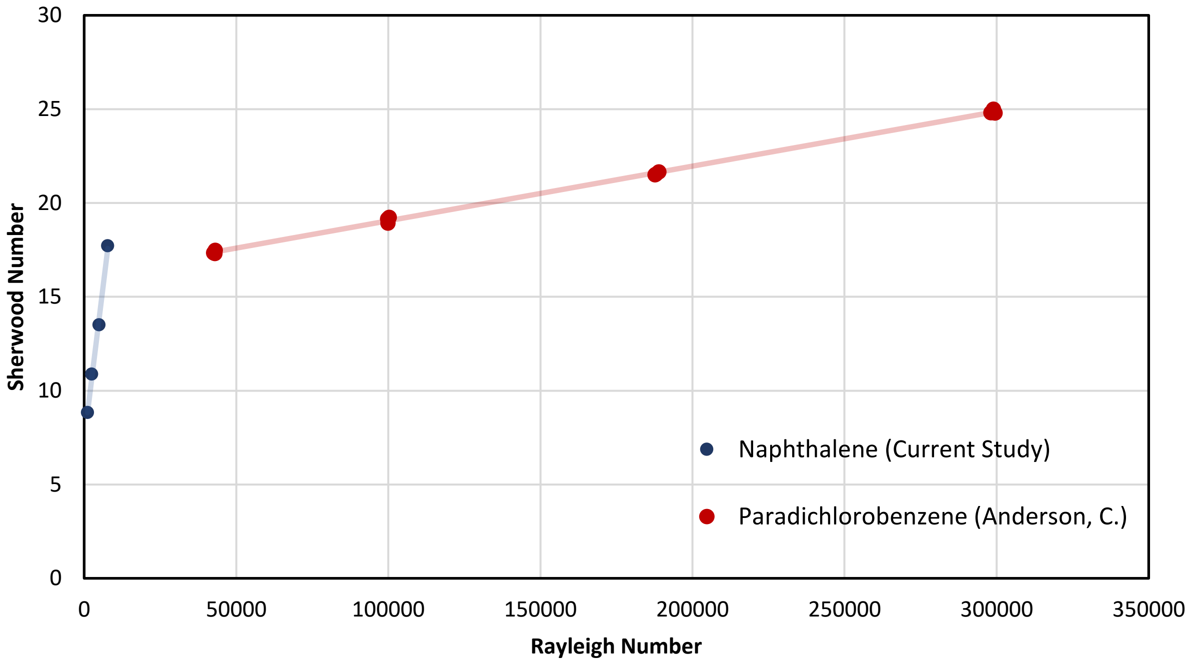

Figure 11: *Comparison of the Sherwood number as a function of the Rayleigh number for naphthalene and paradichlorobenzene [4] spheres of diameter 30 mm, 40 mm, 50 mm, and 58 mm.*

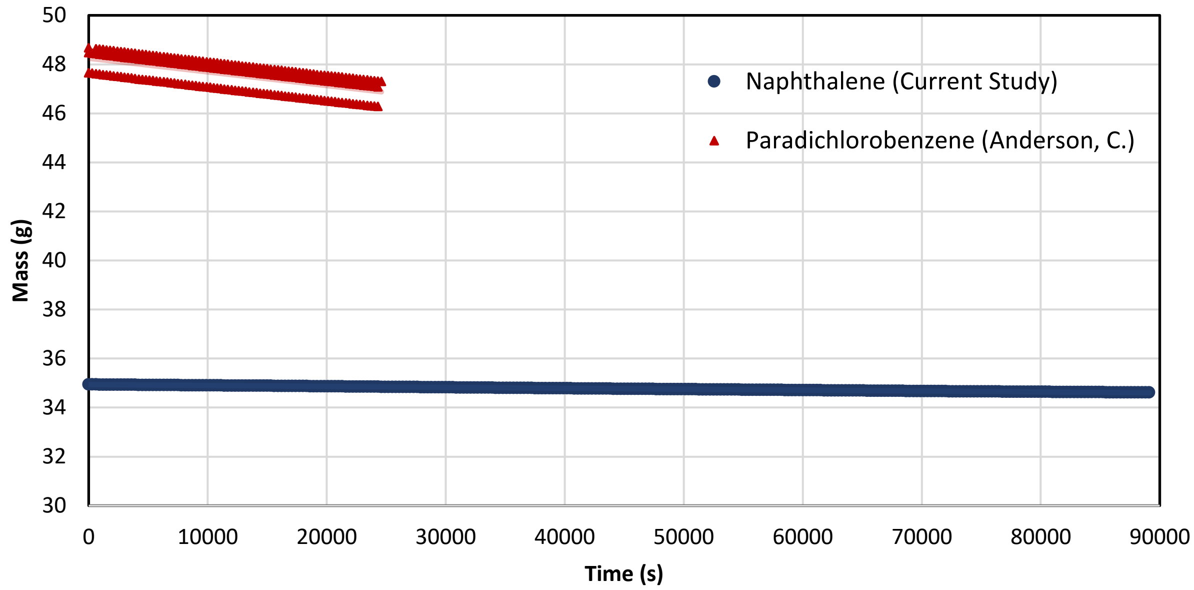

Figure 12: *Comparison of the mass transfer rates of 30 mm diameter naphthalene and paradichlorobenzene [4] spheres.*

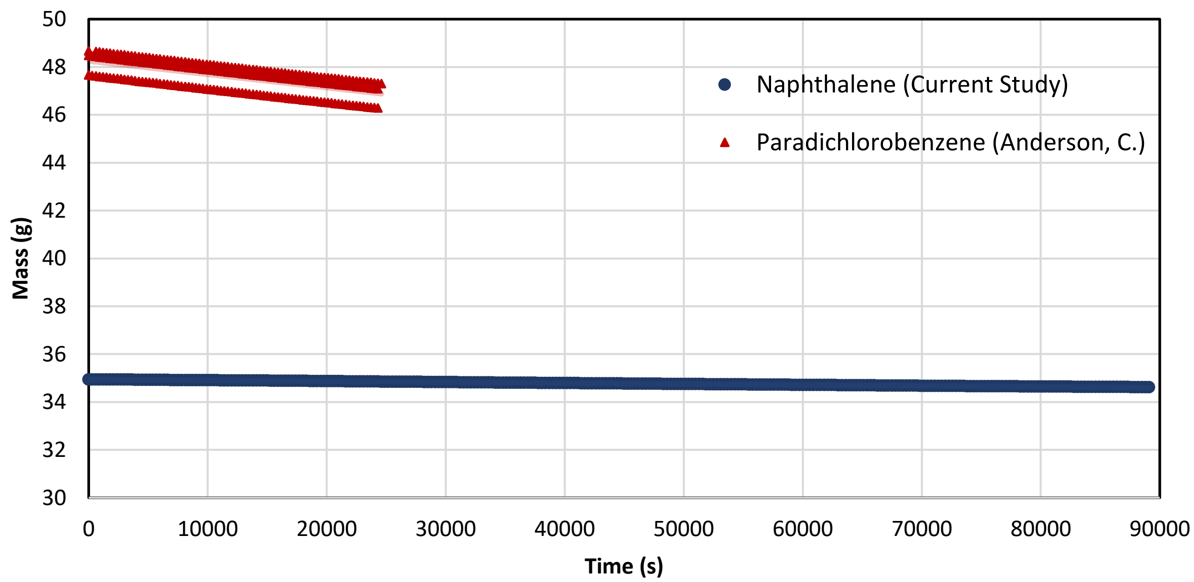

Figure 13: *Comparison of the mass transfer rates of 40 mm diameter naphthalene and paradichlorobenzene [4] spheres.*

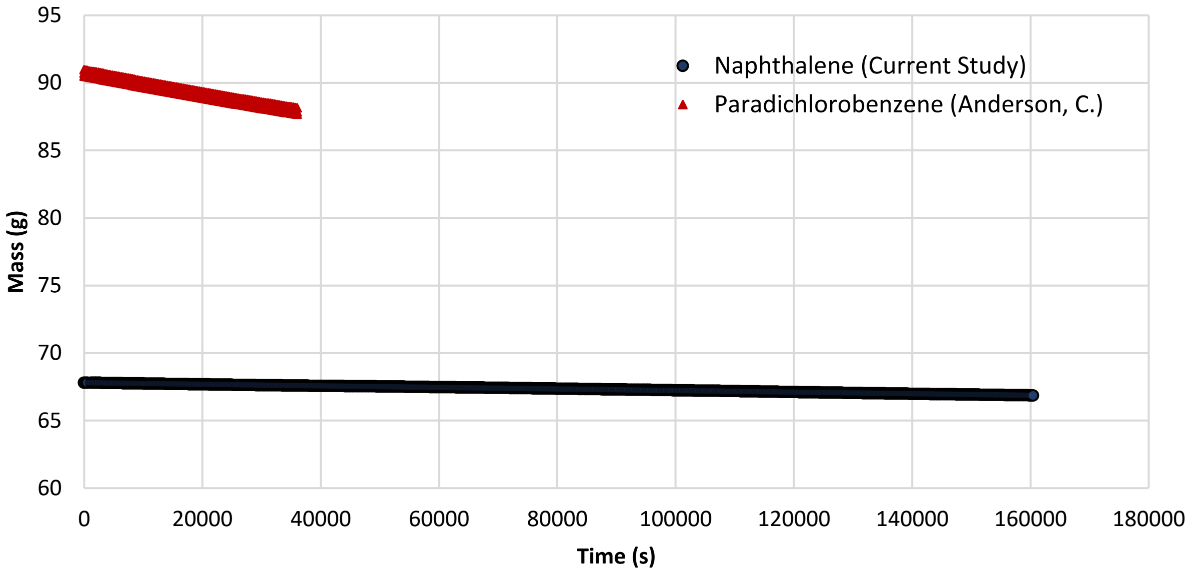

Figure 14: *Comparison of the mass transfer rates of 50 mm diameter naphthalene and paradichlorobenzene [4] spheres.*

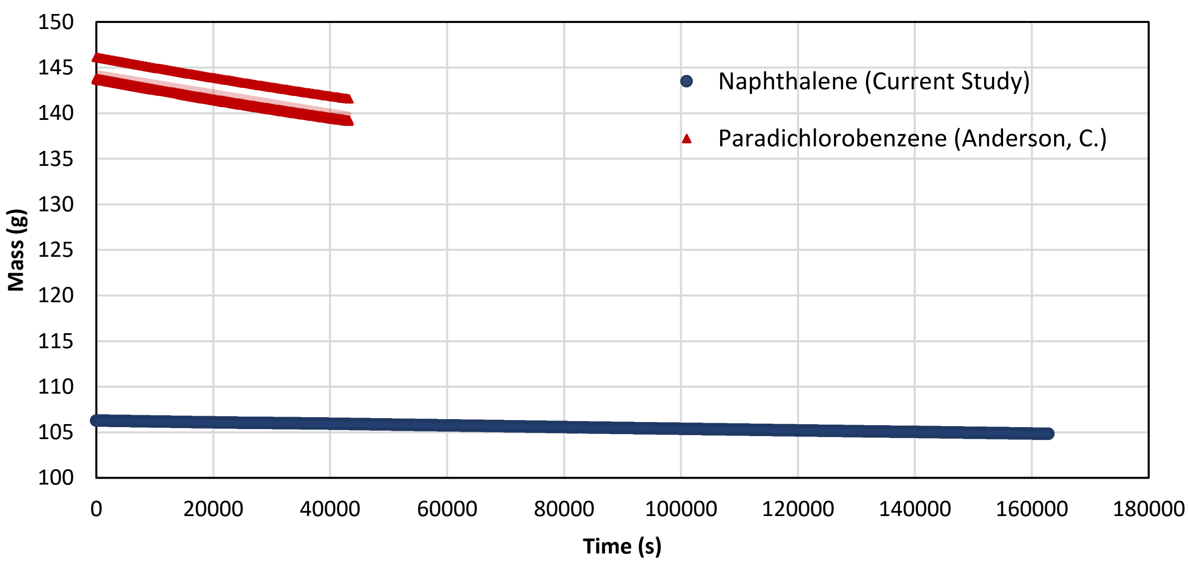

Figure 15: *Comparison of the mass transfer rates of 58 mm diameter naphthalene and paradichlorobenzene [4] spheres.*