Thermal Stress Simulation on a Stainless-steel Submersible Water Heater design

S K Singh1,3, G Alok1,2, R Ande1, C Pravalika1, N Sindhuja1 and J Uday1

1Centre for Design, SR University, Warangal, Telangana, India
2Department of Civil Engineering, SR Engineering College, Warangal, Telangana, India
3Department of Mechanical Engineering, SR Engineering College, Warangal, Telangana, India

Corresponding author: shailen104@gmail.com

Abstract. A new design of immersion heater is proposed for common household use and is checked for stress induced due to heating and the corresponding factor of safety (FOS). Temperature distribution with time is obtained by building a finite element model of the simplified heater geometry (body) while considering conduction and convection due to buoyancy effect. For realistic results, a two-step analysis is done. Firstly, the temperature distribution with time, is calculated in Solidworks® Flow Simulation software by considering the conduction in heater body and convection in the surrounding water. Secondly, the calculated temperatures are exported into Solidworks structural simulation and thermal stresses are calculated. An effort is made to study the effect of purely thermal stresses on the heater body as it is heated under 3000 W power and visualize the flow trajectory of fluid particles as it is heated. The results are used to assess the stress, strain, and FOS of the design and to finalize its geometry. It is concluded in the study that buoyancy effects and flow trajectory of fluid particles is paramount in determining the thermal stresses in a heater design.

1. Introduction

Immersion heaters are an integral part of common household environment in colder seasons. Commonly available immersion heaters in India come in the price range of around 200 to 500 INR which does the job of heating a bucket of water for bathing. The problem is that these types of heaters are cumbersome to use compared to the expensive counterpart (geyser). There is also generally no temperature control or thermostat in the cheaper versions. There seems to be a social stigma attached too which presumes that these type of immersion rods are only used by lower income households. Hence, an effort is made to design a submersible heater which looks like a premium product and can be used in a variety of water heating applications including in a medical setup.

In a commercially available tubular heater, Nichrome wire supplies heat through the surrounding Magnesium dioxide powder which is commonly installed in a stainless steel or copper tube [1]. The Magnesium dioxide powder is compacted when the surrounding tube is drawn through a wire drawing machine which increases the thermal conductivity of the powder. As is widely known, heat can be transferred in three modes which are conduction, convection, and radiation [2]. Conduction and convection are predominantly active at lower temperatures whereas radiation is only significant at very high temperature and does not require even a medium to transfer heat unlike the former two modes.
Conduction happens in solid medium such as metals and nonmetals whereas convection happens in fluid medium such as water and air. In conduction, heat is transferred by molecular vibration where there is no net movement of the particles of solid. Convection involves actual bulk movement of fluid particles from one point to another which carry heat. In this study, since we are dealing with lower temperatures in heating water, only conduction and convention are relevant. Conduction happens in the heater body and convention happens in the water which surrounds the heater. The convection effects which give rise to bulk movement of water particles also called as buoyancy, contributes a significant part in dispersing the heat generated by the heater thereby reducing the thermal stress induced in the heater casing.

To consider the convection or buoyancy effects, this study is carried out in two parts. First, the temperature distribution over time in heater body is obtained, by using Solidworks Flow Simulation®, considering the conduction and convection in heater body and water, respectively. Then, in the second part of the study, this temperature distribution is used in structural study to find the thermal stress induced. The study setup and parameters involved in Solidworks mechanical and flow study is listed in further sections.

2. Literature survey
Thermal analysis in Solidworks simulation is known to give reliable results as can be seen in numerous research publications. Paul [3] demonstrates how to set up flow simulation in solidworks and subsequently validates the results with analytical and empirical results. John [4] has documented a structured approach in setting up the thermal study while utilizing the convection effects induced by heating a component.

Whenever fluid is involved in a study (liquid or gas), the effects of buoyancy become significant as is also noted in the present paper. Studies, both with and without convection effects were set up and there was a significant difference in the temperature distribution in solids and fluid involved in the current study, although the difference is not documented in the presented text. Solidworks flow simulation shows the particle trajectories as water begins to heat up which induces the convection currents, significantly affecting the local temperatures. So, any study involving fluids must consider the convection and conduction effects for calculating the temperature distribution. Peng [5] conducted thermal analysis simultaneously on identical components in Solidworks simulation and ANSYS workbench thereby evaluating the results.

Tubular heaters have been used extensively in a wide variety of applications because of their ability to be morphed or bent in any shape, provided a minimum bend radius is satisfied. A lot of research has also been carried out to improve their efficiency by creating it out of different coatings, composites and nonmetals [6][7][8]. An instant water heater is designed by Liu [9] based on dual helical coil while also using a screw tape to modify the flow characteristics of water in the heater body, thereby increasing the heat transfer and hence efficiency. Similar approach is utilized by others to improve the efficiency [10][11]. Other methods of increasing the heat transfer in tubular heaters such as, adding baffle and obstruction in the flow of water is also been utilized [12][13]. Numerical simulation tools have been effectively used to evaluate heat transfer in mechanical components as studied by Praveena [14] and Gopikrishna [15]. Some of the research and visuals generated in this study are also utilized to teach the students of product design, importance of multi-disciplinary Engineering Design Process (EDP), as proposed by Alok [16] and Santosh [17].

3. Product design methodology

3.1. Need Identification
The problem identified with the commercially available immersion heaters for home use, is that these must be clipped on top of the bucket wall. Because of this, the water must be filled to the top, even when there is no need to heat that much water. This wastes significant energy, which could otherwise be saved [18]. Also, the currently available designs need the bucket to be in a certain size and shape, for these heaters to work at all. Added to this, the design does not attract premium customers who almost always prefer a geyser, which also wastes more energy than is required. Also, without a
thermostat the currently available products waste energy more than necessary. The inability to set the desired temperature is also an inconvenience to the user since they need different temperatures with the ever-changing weather. Thermostat controlled adjustable temperature functionality is also useful in physiotherapy and clinical needs where a product like this could be effective.

3.2. Proposed Solution
The proposed design intends to address the said shortcomings, in the presently available immersion heater for home use. The proposed design has an aesthetic appeal, which attracts both common household and rich customers alike. The size, form and function of the proposed design, eliminates the need to clip it to water container and be submerged into the container instead. The device is supposed to heat water in container of any size and shape, as long as it is completely submerged into it.

Additionally, the proposed design also includes a thermostat which maintains the set temperature thereby preventing overheating. This in turn saves further energy even if it is left unattended for long period of time. The design is also compact, which can be carried wherever desired and heat water in practically any container.

3.3. Conceptualization
The proposed design has the form of a cylinder which can be submerged into water which is to be heated, as seen in figure 1. As long as it is completely submerged in the fluid, it can be left standing upright or laid on its side. The Top surface has a display which indicates the temperature and buttons to increase or decrease the set temperature. The top compartment houses the electronics and the microcontroller which controls the operation of the device. The upper and lower compartments are insulated from each other, to prevent considerable heat transfer from the lower compartment (incorporating the heating element) to the upper compartment.

![Figure 1. A CAD model of the proposed design.](image-url)
The lower compartment has a Nichrome heating element, which is wound on the ceramic core which holds it in place. Surrounding the core is the MgO (Magnesium Oxide) powder which conducts heat to the outer casing. The Heat is conducted through the compacted MgO powder and the surrounding steel casing. This heat is finally transferred to water by convection. However, for analysis purpose, heat is assumed to be generated from a solid ceramic core which is covered by a steel casing, without any thermal resistance, so all the heat is readily transferred to the surrounding water.

4. Methods and Materials

4.1. Study methodology
The study is to be carried out in 2 steps due to the involvement of convection effects in the water, surrounding the heater. Once the temperature distribution over time is obtained from the Solidworks® Flow simulation software, it is exported in Solidworks structural study, for obtaining the stress distribution due to the temperature effects. It is important to note that just Solidworks thermal or mechanical study cannot individually determine the thermal stress, due to the thermal buoyancy effects in water. Table 1 tabulates the material properties of the components involved in both flow and mechanical study.

| Component       | Material Properties                       |
|-----------------|------------------------------------------|
| Water container | Polycarbonate, Mass: 968.97 gram          |
| Fluid to be heated | Water, volume: 19.436 liter            |
| Heater core     | Alumina (99.9%), Mass: 217.84 gram       |
| Heater casing   | Stainless steel (AISI 304), Mass: 24.68gram, Wall thickness: 2mm |

4.2. Geometry Simplification
The heat is supplied using a solid cylinder (instead of Nichrome wire and MgO Powder) and the geometrical intricacies of a typical tubular heater are not considered for simplifying the study. The cylindrical geometry which is supposed to be constructed out of a solid ceramic core, Nichrome wire and MgO powder, is assumed to be made of ceramic core only. From this alumina core, 3000W of heat is generated, as shown in figure 2. This assumption is justified since the effects of thermal stresses on the casing of heater are to be studied, irrespective of the ceramic core or the heating element wire.

Figure 2. Dimensional details of the flow study setup.
4.3. Flow study setup
Since both conduction and convection is to be accounted for, in the solids and fluids in the study, a flow study is to be conducted and a mere mechanical/thermal study would not be sufficient. To obtain accurate temperature distribution with time, Solidworks Flow simulation is done, and the buoyancy phenomena is quantified. Both conduction and convection is turned on in the flow study as shown in table 2. The maximum, minimum and bulk temperature with time are plotted and tabulated in later part of this paper. The initial solid and fluid conditions are also tabulated in table 3. The surrounding temperature is assumed to be 35.05 °C throughout the study and the junction heat transfer coefficient is set as 25 W/m²/K.

| Parameter                  | Condition                      |
|----------------------------|--------------------------------|
| Conduction in solids       | On                             |
| Flow Type                  | Laminar and turbulent          |
| Time-Dependent             | On                             |
| Gravity                    | On                             |
| Radiation                  | Off                            |

**Table 2.** Flow study parameters in Solidworks® Flow Simulation.

**Table 3.** Initial Conditions for Solidworks® flow study.

| Initial condition          | Value                                      |
|----------------------------|--------------------------------------------|
| Thermodynamic parameters   | Static Pressure: 101325.00 Pa  |
|                            | Temperature: 25.05 °C                        |
| Solid parameters           | Material: Polycarbonate                     |
|                            | Initial solid temperature: 20.05 °C        |
| Heat transfer coefficient  | 25.000 W/m²/K (constant)                    |
| External fluid temperature| 35.05 °C (constant)                         |

4.4. Mechanical study setup
The temperature distribution obtained from the flow study is imported in Solidworks® Mechanical study to find the thermal stresses induced in the heater casing with time. It should be emphasized that the mechanical load and hence stresses are zero in the heater casing since neither external load nor any support reactions exist in this setup. The only support provided to the heater casing is “roller type” which does not offer any longitudinal or lateral resistance. Longitudinal (along the major axis of the cylindrical heater body) mechanical stresses are absent since there is no reaction from the top surface, which is free to move in the vertical (and horizontal) direction. Hence, all the stresses are thermal in nature which are in fact, imported from the flow study. Table 4 lists the mechanical study parameters which also highlights the solid mesh used.

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Analysis type              | Static                                     |
| Mesh type                  | Solid Mesh                                 |
| Thermal effect             | On                                         |
| Thermal option             | Include temperature from Flow Simulation   |
| Zero strain temperature    | 298 Kelvin                                 |
| Contact type               | Bonded                                     |
| Solver type                | Automatic                                  |

**Table 4.** Solidworks® Mechanical study parameters.
5. Results
Flow trajectories of the particles, as shown in figure 3 show a specific pattern because of the buoyancy effects induced as the water heats up. When heat is supplied to water, the warm particles slowly move up and the cold particles come down due to the density difference between hot and cold fluid particles, thereby improving the heat distribution. It also reduces the heat concentration near the heater surface, reducing the thermal stress in the heater wall, which eventually improves its service life.

![Temperature distribution in heater core, casing and container superimposed on flow trajectories of water particles.](image)

As can be seen in the figure 4, the temperature is highest in the lower portion of heater body. This can be attributed to less movement of water particles in the lower portion of the container as compared to the upper portion, which is also evident from the color of the flow trajectory of particles. Better movement of fluid particles in the upper region of container due to density differences, allows more heat to be carried away from the heater walls, reducing its temperature. As it can be seen in the flow trajectory of the particles, these not only move vertically but also radially away from the heater surface, carrying heat away from it, more effectively again, in the upper portion of the water container.

As expected, it can be seen in figure 4, that the fluid (water) temperature is the highest right above the heater body and lowest at the surface of the container. The bulk temperature of the water is highest in the uppermost region of the container and lowest in its bottommost region. The fluid movement is also highest in the upper most region as can be seen in the flow trajectories of water particles. The figure 4 is captured at about 42nd minute at which the fluid comes to boiling state near the heater body. Figure 5 shows the maximum, minimum and the bulk temperature of the heater core (as against heater casing) which is heating the water at a rate of 3000W. As can be seen in the plot, the temperature starts to normalize after the convection and buoyancy effects have developed, which forces the hot and cold fluid particles to mix effectively. Because of the convection effects in water, the heater can even be laid down, with the heat distribution still being effective. Because of this effect, a small quantity of water can be heated with the current design, as long as it is completely submerged in the water. This reduces the electricity usage, which would have been wasted, had the entire container been filled to the top.
Figure 4. Temperature distribution in water superimposed on particle trajectories.

Figure 5. Heater core temperature plotted with time.

Figure 6. Heater casing temperature plotted with time.

The plot in figure 6 shows the maximum, minimum and bulk temperature of the heater casing (as against heater core) over time. The contact between heating element (core) and heater casing (body) is assumed to be bonded with no thermal contact resistance. Hence, all the heat generated in the heater
core is assumed to be transmitted to the casing and in turn to water. Besides, the amount of heat absorbed by the core before reaching steady state, is negligible compared to the total heat supplied to the water in this study, hence can be neglected. The bulk temperature is close to 200 degree centigrade when the water comes to boiling. The maximum thermal stress induced in the heater casing, as will be seen in second part of this study, is within the safe limits and the factor of safety (FOS), calculated from the static structural study is 1.17 as is shown in figure 9(b).

The plot in figure 7 shows the maximum, minimum and bulk temperature of water as calculated by Solidworks® Flow Simulation, considering the conduction and convection effects. The water starts to boil in about 40 minutes which should not happen in the actual device, due to the use of a thermostat and temperature controls. This functionality also allows the device to be used in medical industry, which need the temperature to be appropriate for a variety of physiotherapy procedures.

Table 5. Maximum, minimum, and bulk temperature of heater core, casing and water.

| Temperature (°C) | Time   | 10 min | 15 min | 20 min | 25 min | 30 min | 35 min | 40 min |
|------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Core temp.       | Min.   | 86.3   | 100.4  | 114.4  | 127.4  | 140.6  | 154.3  | 165.9  |
|                  | Max.   | 399.1  | 409.2  | 422.0  | 423.7  | 416.5  | 403.5  | 395.8  |
|                  | Bulk   | 184.5  | 197.3  | 210.4  | 220.5  | 227.6  | 234.8  | 241.8  |
| Casing temp.     | Min.   | 65.1   | 78.7   | 93.0   | 106.7  | 119.7  | 133.6  | 146.3  |
|                  | Max.   | 391.2  | 401.4  | 414.0  | 415.7  | 408.7  | 394.6  | 388.4  |
|                  | Bulk   | 153.6  | 166.1  | 179.3  | 189.1  | 195.0  | 201.1  | 210.7  |
| Water temp.      | Min.   | 35.8   | 47.1   | 58.1   | 68.4   | 78.0   | 88.2   | 98.2   |
|                  | Max.   | 64.0   | 72.7   | 80.6   | 89.9   | 94.4   | 103.5  | 113.5  |
|                  | Bulk   | 41.1   | 52.0   | 62.7   | 73.2   | 83.5   | 93.7   | 103.8  |

Table-5 consolidates the maximum, minimum and bulk temperature of heater core, casing and water in the container, at chosen time milestones, as calculated by Solidworks® Flow Simulation study. Bulk temperature of water reaches about 63 °C in 20 minutes and about 73 °C in 25 minutes, which is appropriate for current design goals. It should be noticed that these temperatures are for about 20L water in the container and the results will be quicker, when working with less water as desired.

Figure 8(a) shows the Von Mises stress distribution at about 41 minutes and the original geometry is superimposed over the deformed result, which is shown magnified with a scale of 42.65. It was also apparent from the results of flow simulation, which indicated that temperature was significantly higher in the lower portion of the heater because of the relatively still water in that region. As a result, stress and deformation is predominant in the lower portion of the heater casing. Figure 8(b) shows the resultant deformation of the heater casing superimposed over the original geometry, magnified with a scale of 42.65. The maximum value is 0.392 mm which is within the acceptable limits. The deformation is least at the bottom because a roller support is applied as can be seen by the arrows.
Figure 8. (a) Maximum Von Mises stress in the heater casing; (b) Resultant deformation superimposed on the original geometry.

Figure 9. (a) Equivalent strain in the heater casing; (b) FOS of the heater casing.

Figure 9(a) shows the equivalent strain in the heater casing and as expected it highest in the region where the temperature is the highest. It can be seen with the flow trajectories of water particles, that in the lower portion of the water volume, the movement is minimal and hence the heat is not carried forward as effectively, as in the upper portion. Figure 9(b) shows the Factor of Safety distribution in the casing of the newly designed heater. As was apparent from the temperature distribution in flow simulation, the FOS is lowest in the area of higher heat concentration. A minimum FOS of 1.17 is observed in the lower region of the heater, which showed the maximum temperature in flow
simulation. By this insight, we can take appropriate action in further modifying the design of this heater in future iterations. Studies can also be done on other variations of stainless steel and casing wall thickness. AISI 304 stainless steel is a good fit in terms of formability, corrosion resistance, yield strength and cost as can be observed from material data at METWEB [19] and cost at Onlinemetals [20].

6. Discussion
From the results obtained in the Solidworks® Flow and Thermal stress simulation, it can be seen that convection/buoyancy effects significantly affect the results. Preliminary studies were done prior to the study presented and it was clear that temperature, and thus thermal stress distributions, were nowhere near the results which are presented in this paper. And without considering the buoyancy effects, the temperature distribution which is required to be obtained for a successful design, could not be efficiently obtained. Buoyancy effects were also important to find out the time required to reach a certain bulk temperature, which is important to determine the heater power and sizing. The form factor and service conditions of this submersible heater also necessitates a steel grade which is efficiently formable and corrosion resistant, which is very well met by AISI 304 as per the product research done. The bulk movement of water also determines the part of the heater which is stressed more because of the temperature difference and is also apparent from the thermal stress and strain obtained in this study. The design parameters obtained can be summarized as:

- The time required to reach a bulk temperature of about 63 degrees is 20 minutes and for 73 degrees is 25 minutes which is within the design criteria.
- To provide this functionality, the heat supplied is to be 3000 W and the thermal stresses induced in the heater body/casing are within acceptable limits. The minimum FOS with these parameters is 1.17.
- The suitable material is observed to be AISI 304 stainless steel which has the correct combination of formability, yield strength, corrosion resistance and cost.

7. Conclusions
The thermal stress induced in the newly designed concept of a submersible heater is successfully studied, and the design is observed to be safe with the current design goals. The effects of convection in a heating application are observed to be paramount and is found to impact the design significantly as seen in Solidworks® flow simulation. The buoyancy effects induced due to the difference between densities of hot and cold fluid are successfully observed and plotted. Since the CAD/Simulation model developed in Solidworks®, considers conduction and convection, it should represent the results comparable with the actual physical environment. As a future scope of this product development, further prototyping and testing results can be compared with the presented results.

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