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The Prediction of the Heating Parameters Across the Cooking Vessel of the Large Scale Accelerated Pressure Cooker

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ABSTRACT:

Cooked food is the basic need of human being. Cooking is a physic-chemical endothermic process and hence it requires thermal energy. The present research reveals the estimation of heating parameters across the cooking vessel of an accelerated type of large scale pressure cooker. The predicted results show that the heat transfer coefficient increases initially and later on decreases continuously as heating is in progress. The velocity of thermo-siphoning convective loops formed inside the cooking vessel decreases continuously as the temperature of vessel contents increases. As the temperature of vessel contents increases, then the temperature gradient between the condensing steam and vessel content decreases and heat transfer rate decreases continuously.

Introduction:

Cooking is the basic need of human life and it requires energy. 31% of the total energy consumption of the world is going to utilize for cooking purpose only (Legros G. et al; 2009). The fossil fuels like LPG, CNG are currently used for carrying out the cooking process. But these fuel sources are limited and depleting steadily (Arijit A. Ganguli et al; 2012, Joshi J. B. et al; 2012). The other fuel sources like agricultural waste, fire wood etc. are not environmentally beneficial. On the other side the prices of fossil fuels are increasing at the faster rate. Therefore, it is need of hour to make the cooking practices more energy efficient so that cooking can be carried out with minimum energy consumption. Even though the energy of the universe remains constant but useful form of energy called exergy is limited and therefore, it is necessary to use it effectively and save it for the future of incoming generations.

Pressure cooker cooks the food faster with less energy consumption as compared to other cooking methodologies like open pan cooking systems but safety is the main concern with the implementation of pressurized cooking on a large scale. The large scale pressurized cooking technology operating in safe mode with minimum energy consumption has been invented (Sunil G. Shingade et al; 2021) and the theme of the present research is to predict out the profiles of various heating parameters across the cooking vessel of that invented pressure cooker. The schematic view of the large scale accelerated pressure cooker has been shown inside the Figure 1. It consists of multiple vessel stacks placed one upon another by maintaining the clearance between each other in order to circulate the steam through an angle of 360^0. Each of the vessel stacks consists of three to four vessels placed in a triangular or square pitch. The entire vessel stack assembly is held together by a central stand. The base of the central stand is of perforated type of plate placed on the inside base of the steaming chamber by maintaining the clearance between them. The entire vessel assembly is enclosed by the steaming chamber. The steaming chamber consists of the basal receptacle and upper double walled jacket. The water is taken inside the base of basal receptacle and placed on the flame directly. As the heat supply gets start, then water taken inside the base of basal receptacle gets heat up, boils and generates steam. The generated steam travels upward, condenses on the outer walls of the vessels and transfers latent heat to the vessel contents and therefore, temperature of vessel contents increases. The profiles of various heating parameters like heat transfer coefficient, velocity of the thermosiphoning convective loops formed inside the cooking vessel, temperature gradient between the condensing steam and the vessel contents, the heat transfer rate have been predicted because these are necessary to evaluate the performance of the invented cooker. As per the invented cooking methodology, thermal energy is needed to raise the temperature of water content of the cooking vessel to the temperature at or above the 95^0C and further there is no need of heat supply, because sensible heat content inside the water at or above 95^0C is sufficient for carrying out the cooking process to the completion. Once the heating operation is terminated, then the high temperature water having lower density resides upper side and low temperature water having higher density resides lower side in the cooking vessel. Therefore, vertical temperature gradient gets develop inside the cooking vessel. The invented cooker has been designed in such a way that the temperature inside the bed of food grains should be more than or equal to 95^0C even after terminating the fuel supply so that initiation of the cooking of hard lentils also takes place. Once the heat or fuel supply is terminated, then also the high pressurized steam exist inside the steaming chamber and it gets condense, transfers latent heat and heats up the lower side water content of the vessel to the temperature at which the cooking inside the bed of food grains starts to occur. If the cooker operates at atmospheric pressure, then the condensation of steam after terminating the fuel supply allows outside air to enter inside the steaming chamber and therefore cooling effect gets occur and it is undesired. This technical hurdle can be avoided by carrying out the cooking under pressurized condition. The steam generated inside the steaming chamber of an accelerated pressure cooker is at elevated temperature and elevated pressure. Therefore, temperature gradient between condensing steam and vessel content increases and as a result the rate of heat transfer increases. Another technical advantage of elevated pressure is that the rate of steam condensation increases and therefore heat transfer occurs at faster rate.

Research and Methodologies:

Numerical method has been used to solve the heat balancing equation to predict out the heating parameters across the cooking vessel. The invented accelerated pressure cooker operates up to 2 bar of vapor pressure. The saturation temperature of water at 2 bar of equilibrium vapor pressure is of 120^0C. Therefore, the temperature of steam formed inside of the steaming chamber varies from 100 to 120^0C. The average temperature of steam of 110^0C is taken into consideration in performing the simulations.

The cooking vessel of an accelerated pressure cooker has been shown in Figure 2. The base of the cooking vessel is of dished type and inside base of the vessel is covered by perforated plate or fine wire mesh. It consists of three sections. Section I is located below the perforated plate and it contains free water only. Section II is located above the perforated plate and it consists of the bed of food grains along with water inside its voidage. Portion III is located above the bed of food grains and it contains free water only. The indistinct thermo-siphoning water loops get form across all these three sections instead of forming distinct or separate loops in each of the sections which increases heat transfer coefficient across the bed as shown in Figure 2 and it is taken into consideration for performing the simulations. The velocity of the circulating convective loop has been estimated by doing the energy balance along its circulating path.

Results and discussion:

The energy balance along the circulating thermo-siphoning convective loops has been done as follows:

$$(\rho_1 - \rho_{110\ 0C})gH = \rho_{avgo}\frac{u^2}{2} + \frac{180\mu_0(1-\varepsilon)^2}{{d_p}^2\varepsilon^3}Au2h + \frac{7\rho_{avgo}(1-\varepsilon)}{4d_p\varepsilon^3}(Au_0)^2 2h$$

Where h is height of rice bed or any food grains, ε is the voidage across the rice bed and H is the height of water pool. The velocity of the circulating convective water loops (u) has been estimated by solving the above equations.

The rate of cooking varies with temperature and the % cooking occuring per second (%C_{sec}) is given by the following mathematical relation (Rekha et al; 2011)

$$\%C_{sec} = 5\,X\,10^{-5}T^2 - 0.0064\,X\,T + 0.2189$$

Where, T is the temperature in degree Celsius. The overall % cooking (%$C_{overall}$) after 1 sec of initiating the actual cooking process is given by

$$\%C_{overall(1)} = \%C_{\sec(1)}$$

The overall % cooking (%$C_{overall}$) after 2 seconds of initiating the actual cooking process is given by

$$\%C_{overall\,(2)} = \%C_{\sec(1)} + \%C_{\sec(2)}$$

The overall % cooking (%$C_{overall}$) after n seconds of initiating the actual cooking process is given by

$$\%C_{overall(n)} = \%C_{\sec(1)} + \%C_{\sec(2)} + \cdots + \%C_{\sec(n)}$$

As the cooking starts to take place, then the voidage of rice bed reduces. Initial voidage (ε_0) of the cooking bed is equal to be 0.665 and once 100% cooking takes place then it reduces by 58%. Therefore, the resulting voidage of the cooking after 1 second of initiating the actual cooking process is given by

$$\varepsilon_1 = \varepsilon_0 - \frac{0.58}{100}X\%C_{overall(1)}X\varepsilon_0$$

Similarly, the resulting voidage of the cooking bed after 2 seconds of initiating the actual cooking process is given by

$$\varepsilon_2 = \varepsilon_0 - \frac{0.58}{100}X\%C_{overall(2)}X\varepsilon_0$$

As cooking proceeds then the bed of rice expands and hence the height of rice bed increases and by 100% cooking the height of rice bed increases by 3 times. The height of the cooking bed after 1 sec of initiating the actual cooking process is given by

$$h_1 = h_0 + \frac{3h_0}{100}X\ \%C_{overall(1)}$$

Similarly, the height of the bed after 2 seconds of initiating the actual cooking process is given by

$$h_2 = h_0 + \frac{3h_0}{100}\ X\ \%C_{overall(2)}$$

As cooking proceeds, the size of rice particles increases and by 100% cooking it increases by 25%. Therefore, the length of rice particles depends upon the extent of cooking. The initial length (dp_0) of rice particle is assumed to be equal to 3 mm. The length of rice particle (d_1) after 1 second of initiating the actual cooking process is given by

$$d_{p1} = d_{p0} + \frac{25}{100} X\, d_{p0} X\, \%C_{overall(1)}$$

Similarly, the length of rice particle after 2 seconds of initiating the actual cooking process is given by

$$d_{p2} = d_{p0} + \frac{25}{100}\, X\, d_{p0}\, X\, \%C_{overll\,(2)}$$

While carrying out the simulations, it is assumed that once the entire internal steel structured body of the cooker gets heat up to the temperature of steam then steam gets utilize to heat up the vessel content. As the steam condenses on the outer wall of the vessel, then it transfers its latent heat to the vessel contents and vessel contents get heat up.

$$The\ rate\ of\ heat\ absorbed\ by\ the\ vessel\ content = h_1A_1\Delta T + h_2A_2\Delta T$$

Where, h_1 and h_2 are the inside heat transfer coefficients across free water and rice bed respectively, A_1 and A_2 are the heat transfer areas across free water and rice bed respectively and ΔT is the temperature gradient between the condensing steam and vessel content. The heat transfer coefficient across the free water has been estimated as follows:

$$\frac{h_1D_i}{K} = f(Re)f(Pr) = 0.04Re^{0.75}Pr^{0.33}$$

$$Re = \frac{D_iu\rho}{\mu}\ and\ Pr = \frac{C_p\mu}{K}$$

Heat capacity depends upon the temperature and it is given by

$$C_p = A + Bt + Ct^2 + Dt^3 + \frac{E}{t^2}\ , Where, A = -203.606, B = 1523.29, C = -3196.413, D = 2474.455, E = 3.855326$$

$$C_p\ is\ in\ \left(\frac{J}{molK}\right) and\ t\ is\ Temperature(T)(K)/1000$$

As the temperature increases, then the viscosity of water decreases and therefore viscosity of water depends upon temperature and it is given by

$$\mu\ (Pas) = A\ X\ 10^{\left(\frac{B}{T-C}\right)}, A = 2.414\ X\ 10^{-5}\ Pa.s, B = 247.8\ K, C = 140\ K\ and\ T\ is\ in\ K$$

As the temperature increases, then the thermal conductivity of water increases and therefore thermal conductivity of water depends upon temperature and it is given by

$$K = -9X10^{-6}T^2 + 0.0021T + 0.5594\ , Where, K\ is\ in\ \left(\frac{W}{mK}\right) and\ T\ is\ in\ 0C\ : Derived\ from\ the\ known\ data$$

As the temperature increases, then the density of water decreases and therefore density of water depends upon temperature and it is given by

$$\rho = -0.0035T^2 - 0.0772T + 1000.9, Where, \rho\ is\ in \frac{Kg}{m^3}, and\ T\ is\ in\ 0C\ : Derived\ from\ the\ known\ data$$

The inside heat transfer coefficient (h_2) across the bed of rice grains has been estimated as follows (Geb, David et al; 2012):

$$\frac{h_2D}{K} = 0.057((Re)^{0.96})(\mathrm{Pr}^{0.33})$$

It was assumed that initial temperature of water is to be same as the ambient temperature of 25^0C. Further it was also assumed that the heat absorbed by water content of the vessel is going to distribute instantly and uniformly throughout the entire water content of the vessel. The heat balance across the cooking vessel is given by

$$\left(m_1C_{p1} + mC_p\right)\frac{dT}{dt} = h_1A_1\Delta T + h_2A_2\Delta T$$

Where, m_1 and m are the masses of rice and water respectively. Cp_1 and Cp are the heat capacities of rice and water respectively.

$$\frac{(m_1C_{p1} + mC_p)(T_{t+\Delta t} - T_t)}{\Delta t} = (h_1A_1 + h_2A_2)(T_{steam} - T_t)$$

Assume Δt is equal to be 1 sec.

Temperature of the vessel content after 1 second of initiating the heating of vessel content is given by

$$T_1 = T_0 + \frac{(h_{10}A_{10} + h_{20}A_{20})(T_{steam} - T_0)}{m_1C_{p10} + mC_{p0})}$$

Temperature of the vessel content after 2 seconds of initiating the heating of vessel content is given by

$$T_2 = T_1 + \frac{(h_{11}A_{11} + h_{21}A_{21})(T_{steam} - T_0)}{m_1 C_{p11} + m C_{p1}}$$

The simulation approach has been tabulated in Table 1 as follows:

Time (s)	T (^{0}C)	T (K)	Cp(J/kg^{0}C)	K (W/mK)	ρ (Kg/m^3)	μ (Pas)	u(m/s)	Re	Pr	*h_1(W/m^2 K)*
0	25	298.16	4187.48	0.6062	996.7825	0.000890	0.3618	60773	6.1	1139
1	25.832	298.99	4186.87	0.6076	996.5700	0.000873	0.3612	61814	6.0	1148
2	26.663	299.82	4186.28	0.6089	996.3531	0.000857	0.3605	62854	5.8	1157

The variation in heat transfer coefficient with heating time has been shown in Figure 3. It shows that heat transfer coefficient inside the cooking vessel increases initially due to increase in thermal conductivity and reduction in viscosity of water with rise in temperature and later on it starts to decrease due to the reduction in the velocity of circulating thermo-siphoning convective water loops. The predicted profiles of various heating parameters across the cooking vessel of an indirect type of steam cooker operating at atmospheric vapor pressure of the condensing steam have been predicted (Sunil G. Shingade, 2023). The heat transfer coefficient under pressurized heating is comparatively more than that of the normal cooker operating at atmospheric vapor pressure of the condensing steam. It is because of under pressurized heating the sidewall heated water is at comparatively high temperature and therefore, the density difference going to develop between the central water and sidewall heated water of the vessel is comparatively more and as a result the driving force responsible for causing the thermo-siphoning convective loops increases, which finally results into increasing the velocity of circulating convective loops. As velocity increases then the heat transfer coefficient also increases.

The velocity profile of thermo-siphoning convective water loops has been shown in Figure 4. It shows that the velocity of circulating loops decreases with heating time. It is because of as the heating time proceeds, then the temperature of vessel contents increases and therefore, the density difference between the central water and side wall heated water of the cooking vessel reduces continuously which slows down the effect of thermo-siphoning action and as a result the velocity of circulating convective loops decreases.

The variation in temperature gradient between the condensing steam and vessel contents has been shown in Figure 5. It shows that as the heating progresses, then the temperature of vessel contents increases and therefore, the temperature gradient between the condensing steam and the vessel contents decreases continuously.

The variation in the heat transfer rate with heating time has been shown in Figure 6. It shows that as the heating progresses, then the heat transfer rate reduces and it is because of the continuous reduction in the temperature gradient between the condensing steam and vessel contents.

Conclusion:

The heat transfer coefficient inside the cooking vessel of an indirect type of steam cooker is comparatively larger under pressurized heating than that of the normal cooker operating at atmospheric vapor pressure of the condensing steam. The velocity of the thermo-siphoning convective water loops inside the cooking vessel of an indirect type of steam cooker is higher under pressurized heating as compared to that of the normal cooker operating at atmospheric vapor pressure of the condensing steam. The elevated pressure of the steam inside the steaming chamber increases the rate of steam condensation and therefore, heat transfer to the vessel contents takes place faster than that of the normal cooker operating at atmospheric pressure of condensing steam. The dished type base of the cooking vessel increases the bottom surface area of the vessel and as a result overall heat transfer rate increases. The perforated plate or wire mesh placed on the inside base of the cooking vessel allows the heat transfer to take place via convective mechanism only and as a result the entire water content of the cooking vessel gets heat up uniformly in a short time period which accelerates the overall cooking operation.

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List of Figures:

Figure 1: Schematic of an indirect type of accelerated steam pressure cooker

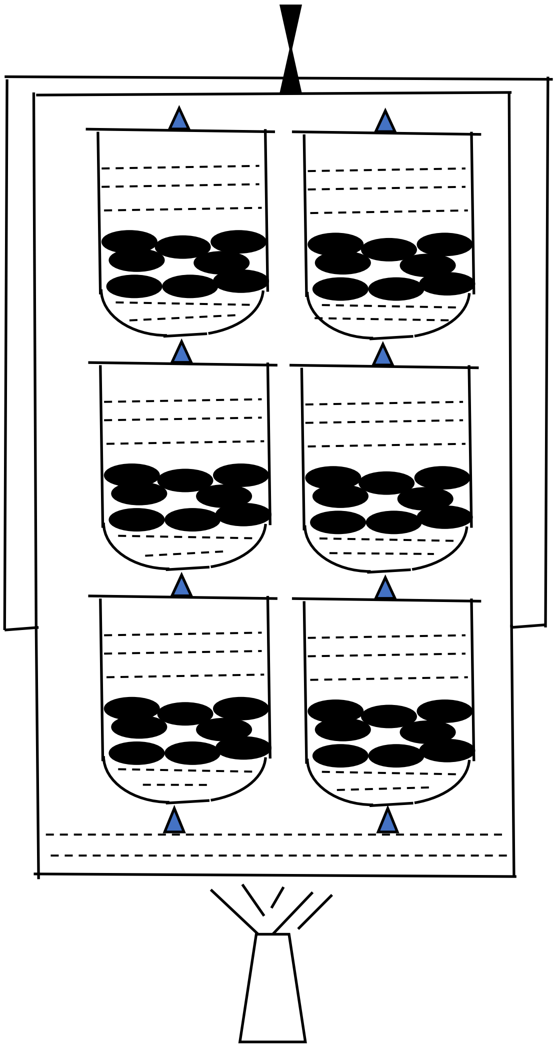

Figure 2: Schematic view of the cooking vessel of an indirect type of accelerated steam pressure cooker

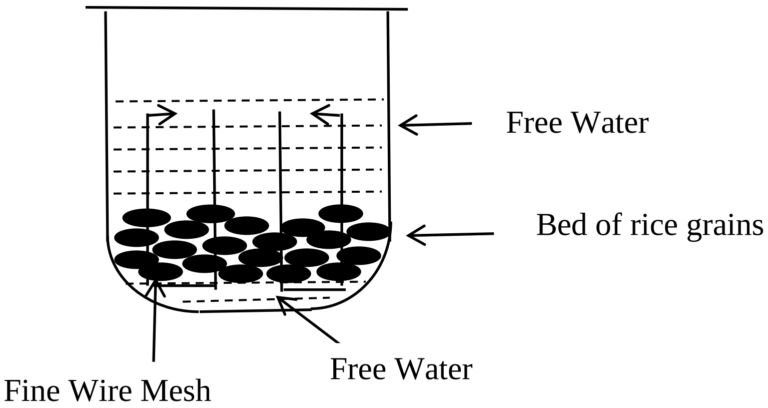

Figure 3: Variation in heat transfer coefficient with heating time

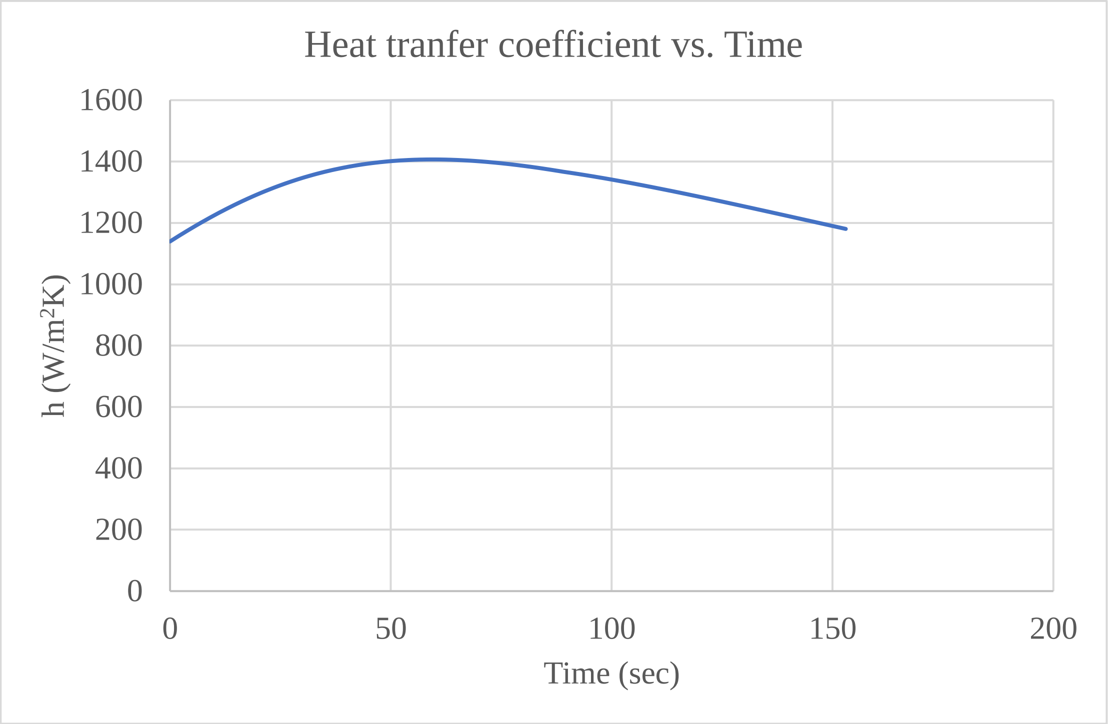

Figure 4: Velocity profile of the convective water loops inside the cooking vessel

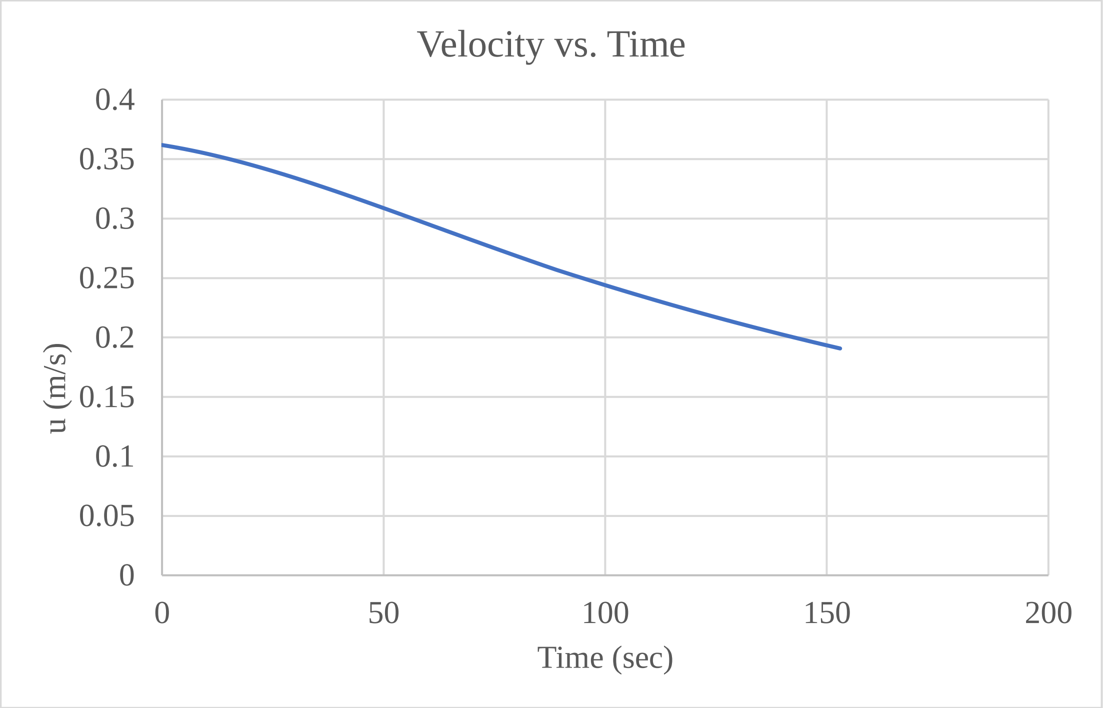

Figure 5: Variation in the temperature gradient between the condensing steam and vessel contents with heating time

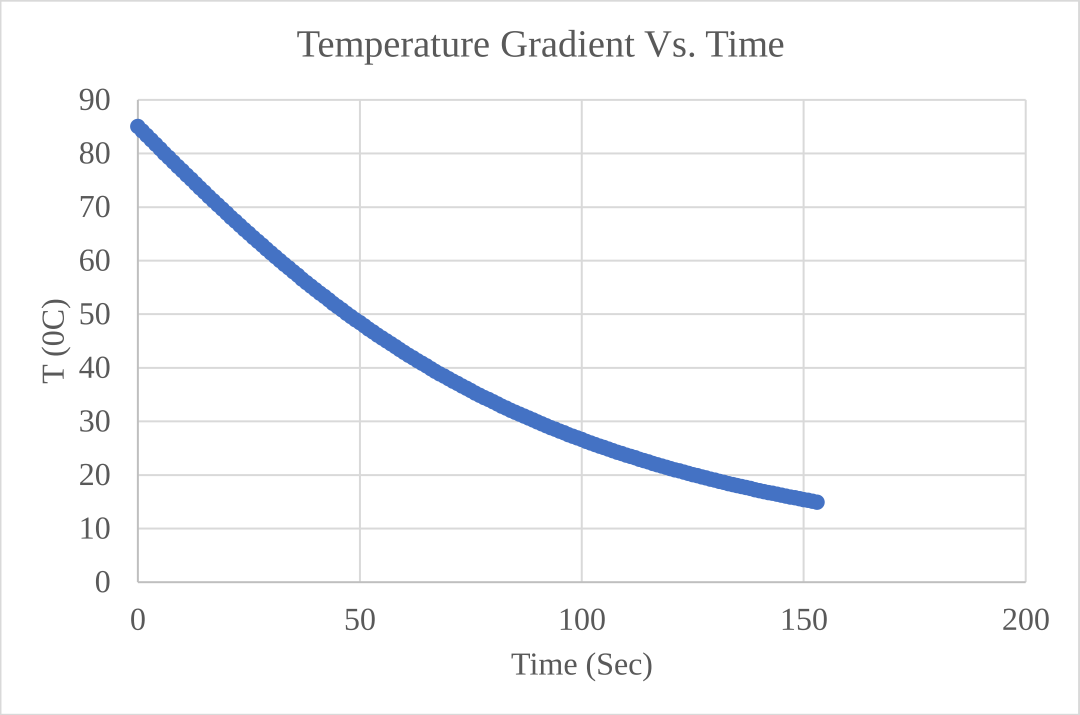

Figure 6: Variation in heat transfer rate with heating time