International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Prediction of the Profiles of Heating Parameters Across the Large Scale Uniform Cooking Vessel of an Indirect Type of Steam Cooker

*Sunil G. Shingade**

Institute of Chemical Technology, Matunga, Mumbai 400019, Maharashtra, India.

ABSTRACT:

Cooking is a basic need of human life and it requires thermal energy to heat up the cooking material to carry out the cooking. The simulations have been performed to predict out the profiles of heating parameters across the large scale cooking vessel while carrying out cooking in an indirect type of steam cooker. The indirect type of steam cooker considered for carrying out the simulations consists of three vessels placed one upon another and each of the vessels contains 3 kg of raw rice and 7.5 kg of water. The heating rate is assumed in such a way that, the entire wall surface areas of each of the vessels being used for transferring the heat simultaneously. The predicted results reveal that heat transfer coefficient initially increases and later on it decrease. The predicted results show that temperature of the vessel contents increases initially at the faster rate and later on the rate of rising temperature reduces continuously. The predicted results show that the velocity of thermo-siphoning convective water circulating loops decreases continuously as the heating operation is in progress.

Introduction:

Cooking is the basic need of human being and it requires thermal energy. There are various types of cooking arts like open pan cooking methodology, direct steam cooking and an indirect type of steam cooking are exist and in practice continuously. Cooking is the largest energy consuming sector in the world contributing 31% of the total energy consumption of the world (Legros et al; 2009). Cooking is an endothermic physic-chemical process and therefore, it is need of hour to make the cooking practices more energy efficient because sources of fossil fuels are depleting steadily (Ganguli et al; 2012 and Joshi et al; 2012). Carrying out cooking on a small scale is an easy task but it is difficult to carry out uniform cooking on a large scale in hospitality sector because temperature dead zones are going to form which lead to non-uniform cooking. The present research is related to the prediction of heating parameters across the cooking vessel which being used to carry out the uniform cooking on a large scale in an indirect type of steam cooker. The indirect type of steam cooker operating at atmospheric steam pressure has been shown schematically inside the Figure 1. It consists of three vessels placed one upon another by maintaining the clearance between each other. Each vessel contains 3 kg of raw rice and 7.5 kg of water because during cooking rice absorbs 2.5 times of water. The entire vessel assembly in enclosed by the steaming chamber and water is taken inside the base of steaming chamber and placed on the flame directly. As heating is in progress, the water taken inside the base of steaming chamber gets heat up, boils up, steam gets generate, generated steam travels upward and condenses on the outer wall surface of each of the vessels. The condensed steam transfers its latent heat to the vessel contents and temperature of vessel contents increases. The suggesting modification for each of the vessels is that the inside base of each vessel is covered by fine wire mesh in order to utilize the entire basal surface area of each of the vessels effectively for heat transfer and to heat up the entire water content of the vessel uniformly. The thermo-siphoning circulating convective loops formed inside the cooking vessel have been shown schematically inside the Figure 2. If the wire mesh is not placed on the inside base of the cooking vessel, then basal surface area of the vessel is not going to utilize for heat transfer entirely because it is partly occupied by water and partly by rice grains. Therefore, there is a possibility of forming dead zones across the cooking bed of rice grains while carrying out the cooking on a large scale. The bed of rice grains causes the resistance to the circulating convective water loops and pressure drop gets occur across the bed and velocity of circulating convective water loop reduces and heat transfer coefficient reduces. The bed of rice grains and chana dal is having the voidage in the range of 65 to 70% but across the toor dal it is of around 35%. Therefore, the bed of toor dal is more compact and hence, more pressure drop gets occur. The dimensional ratios of toor dal and chana dal are shown schematically inside the Figure 3. Chana dal is bigger in size as compared to toor dal and therefore the bed of toor dal is comparatively more compact. From the dimensional ratios of these dals it is observed that H/D ratio for toor dal is very small as compared to chana dal. Chana dal is almost hemispherical in shape while toor dal is almost like a flat dish and therefore the bed of toor dal is comparatively more compact. Therefore, heat transfer coefficient and area of heat transfer across the bed of toor dal is comparatively less and hence the rate of heat transfer is lower which reduces the overall cooking efficiency and also leads to non-uniform cooking. Therefore, the present modification of providing wire mesh across the inside base of each vessel has been suggested to heat up the water content of the bed of hard lentils like toor dal at faster rate. As the wire mesh is placed at the inside base of the cooking vessel then entire basal surface area of the vessel gets utilize for heat transfer and therefore, water below the wire mesh gets heat up at faster rate and passes upward via convection as shown in Figure 2. Therefore, entire water content of the bed of food grains gets heat up uniformly and as a result uniform cooking can be carried out.

Research and Methodology:

An indirect type of steam cooker as shown in Figure 1 has been considered for carrying out the simulations and it consists of three vessels placed one upon another by maintaining the clearance between each other in order to circulate the steam inside the cooker through an angle of 360^0. Each of the vessels is having diameter of 360 mm and height of 140 mm and inside base of the each vessel is covered by perforated wire mesh. Further it was assumed that each of the vessels contains 3 kg of raw rice and 7.5 kg of water. The entire vessel assembly is enclosed by the steaming chamber. The water is taken inside the base of steaming chamber and place on the flame directly. The rate of heat input is assumed to be such that the entire wall surface areas of each of the vessels being used for transferring heat simultaneously right from the beginning of heating of vessel contents. It is assumed that the steam formed inside the steaming chamber is at 100^0C and 1 bar of saturated vapor pressure. The simulations have been performed to predict out the temperature profile inside the cooking vessel, velocity profile of circulating convective water loops inside the vessel and heat transfer coefficient profile inside the vessel. The energy/heat transfer balancing model has been developed and solved numerically to predict out the profiles of above mentioned heating parameters.

Results and discussion:

The cooking vessel of an indirect type of steam cooker containing 3 kg of raw rice and 7.5 kg of water has been shown schematically inside the Figure 2. As the heat supply is started, the water taken inside the base of steaming chamber gets heat up, boils and generates steam. The generated steam travels upward and gets condense on the outer walls of the vessels. The condensed steam transfers its latent heat to the vessel contents and therefore, temperature of vessel contents increases. The transferred heat increases the temperature of wall side water and reduces the density of that heated water. Therefore, density difference gets develop between the central water and wall side heated water of the vessel and as a result thermo-siphoning convective water loops get develop inside the cooking vessel. The energy balance across the circulating convective loops has been done as follows:

$$(\rho_1 - \rho_{100\,0C})gH = \rho_{avg0}\frac{u^2}{2} + \frac{180\mu_0(1-\varepsilon)^2}{{d_p}^2\varepsilon^3}Au2h + \frac{7\rho_{avgo}(1-\varepsilon)}{4d_p\varepsilon^3}(Au_0)^2 2h$$

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

The rate of cooking depends upon the 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 ^{0}C. 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 gets initiate, 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 initial height of the bed (h_0) is equal to be 35 mm and by 100% cooking it increases to 140 mm. 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.

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

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

$$T_2 = T_1 + \frac{(h_{11}A_{11} + h_{21}A_{21})(T_{steam} - T_0)}{m_1C_{p11} + mC_{p1})}$$

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/ mK)*
0	25	298.16	4187.488	0.60627	996.7825	0.00089023	0.22458	75439	6.15	670.5
1	25.2218	298.381	4187.32	0.60664	996.726389	0.00088575	0.22451	75793.72	6.11	671.5
2	25.4434	298.603	4187.155	0.60700	996.669972	0.00088130	0.22444	76148.08	6.08	673.0

The predicted temperature profile inside the cooking vessel has been shown in Figure 4 and it shows that temperature initially increases at faster rate and later on the rate of rising temperature decreases or reduces. It is because of the decreasing rate of heat transfer due to continuous reduction in the temperature gradient between the condensing steam and the vessel contents.

The predicted velocity profile of the convective circulating loop has been shown in Figure 5 and it shows that velocity decreases continuously. It is because of as the temperature of vessel content increases, then the difference between the densities of central water and side wall heated water decreases and therefore, the effect of thermo-siphoning action gets mitigate continuously.

The predicted profiles of heat transfer coefficients have been shown in Figure 6 and it shows that initially heat transfer coefficient increase with time due to increase in thermal conductivity and reduction in the viscosity of water with rise in temperature. But later on it starts to decrease due to the reduction in the velocity of the circulating convective loops.

The scientific reasoning behind placing the perforated wire mesh over the inside base of the cooking vessel is that to utilize the entire basal surface area of the vessel for transferring the heat effectively and to heat up the entire water content of the vessel uniformly to carry out the uniform cooking throughout the entire volume of the vessel. As the perforated fine wire mesh is covered the inside base of the cooking vessel, then indistinct circulating convective water loops get form throughout instead of forming distinct loops across the free water and rice bed separately.

Conclusion:

As the perforated wire mesh is placed over the inside base of the cooking vessel of an indirect type of steam cooker, then heat transfer process can be controlled by convective mechanism only and entire water content of the vessel gets heated up uniformly in a short heating time so that uniform and accelerated cooking can be carried out throughout the entire volume of the cooking vessel even on a large scale by avoiding the possibility of forming temperature dead zones.

References:

1) Arijit A. Ganguli et al; 2012, A novel method to improve the efficiency of a cooking device via thermal insulation, The Canadian Journal of Chemical Engineering, 90, 1212-1223.

2) Geb, David et al; 2012, Internal heat transfer coefficient determination in a packed bed from the transient response due to solid phase induction heating, Journal of Heat Transfer, 134(4), 042604-1 – 042604-10

3) Joshi J. B. et al; 2012, Development of efficient designs of cooking systems II: Computational fluid dynamics and optimization, Indust. Eng. Chem. Res 51 (4), 1897 – 1922

4) Legros G. et al; 2009, The energy access situation in developing countries WHO and UNDP

5) Rekha S. Singhal et al; 2011, Development of efficient designs of cooking systems III: Kinetics of cooking and quality of cooked food, including nutrients, antinutrients, taste and flavor. Indust. Eng. Chem. Res. 51, 1923-1937

List of Figures:

Figure 1: Schematic of an indirect type of steam cooker

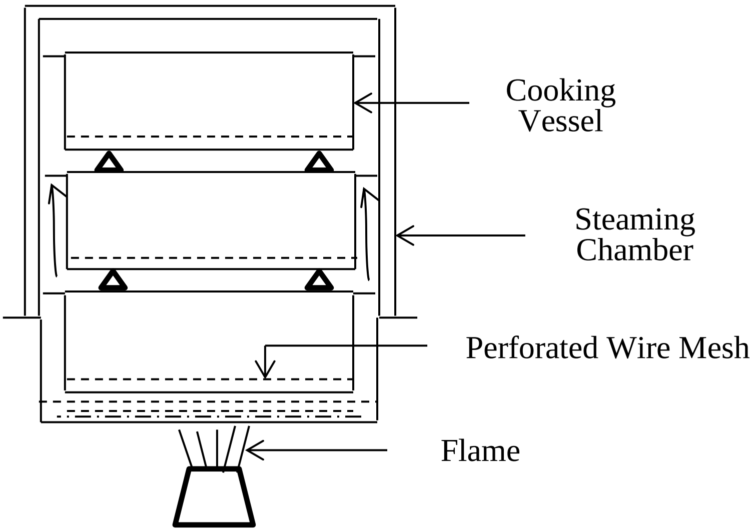

Figure 2: Schematic of cooking vessel

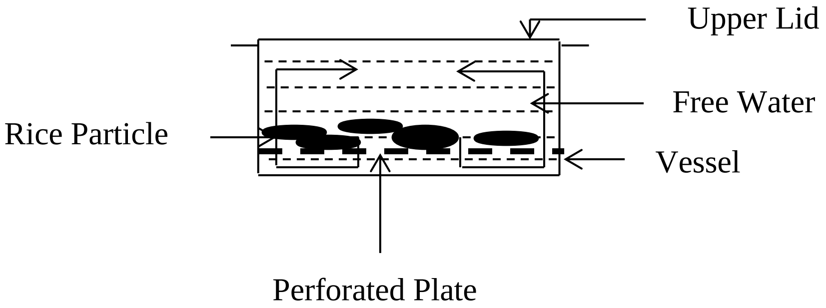

Figure 3: Schematic of Chana Dal and Toor Dal

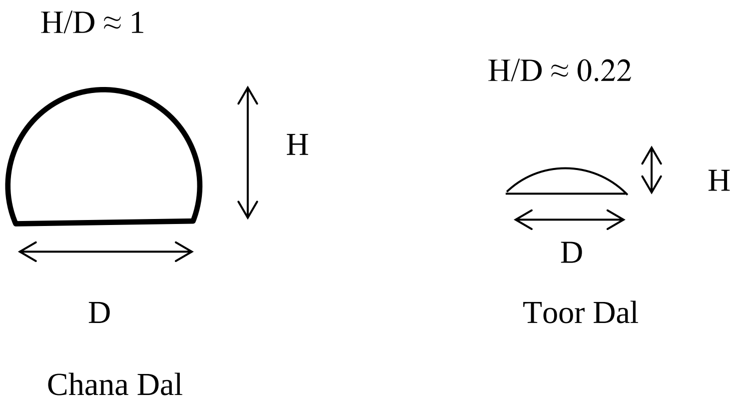

Figure 4: Variation of temperature inside the cooking vessel with time

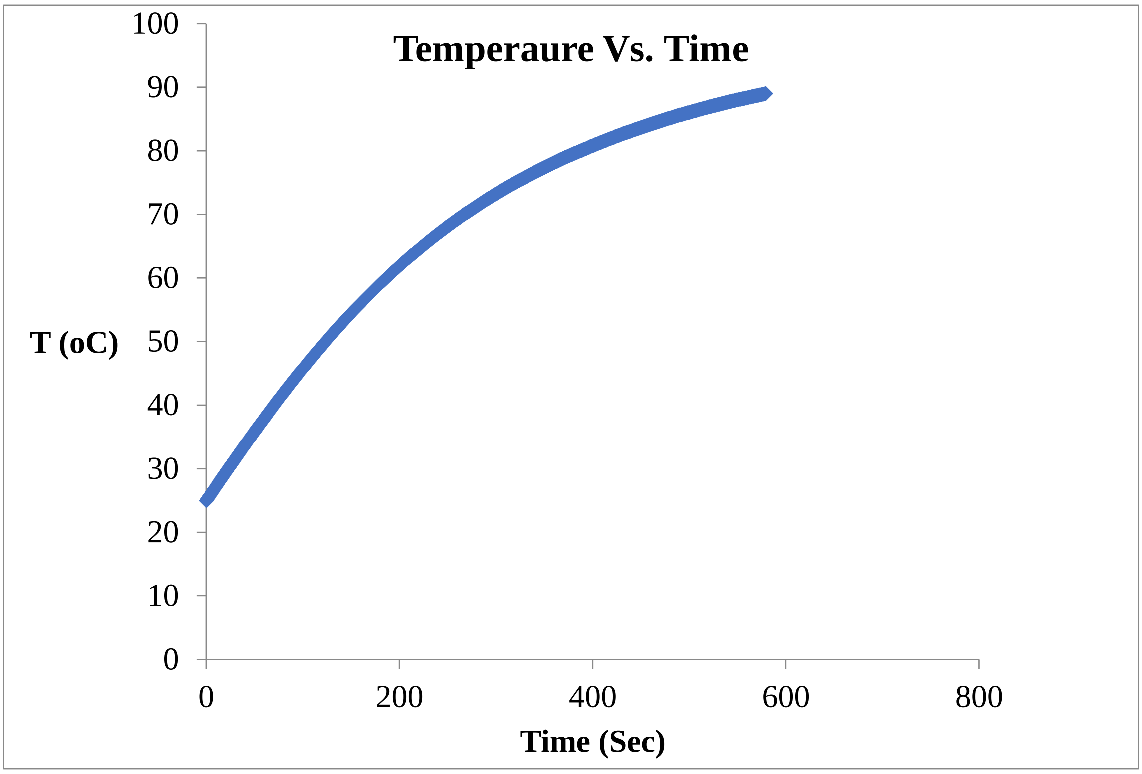

Figure 5: Variation in velocity of circulating convective loop inside the cooking vessel with time

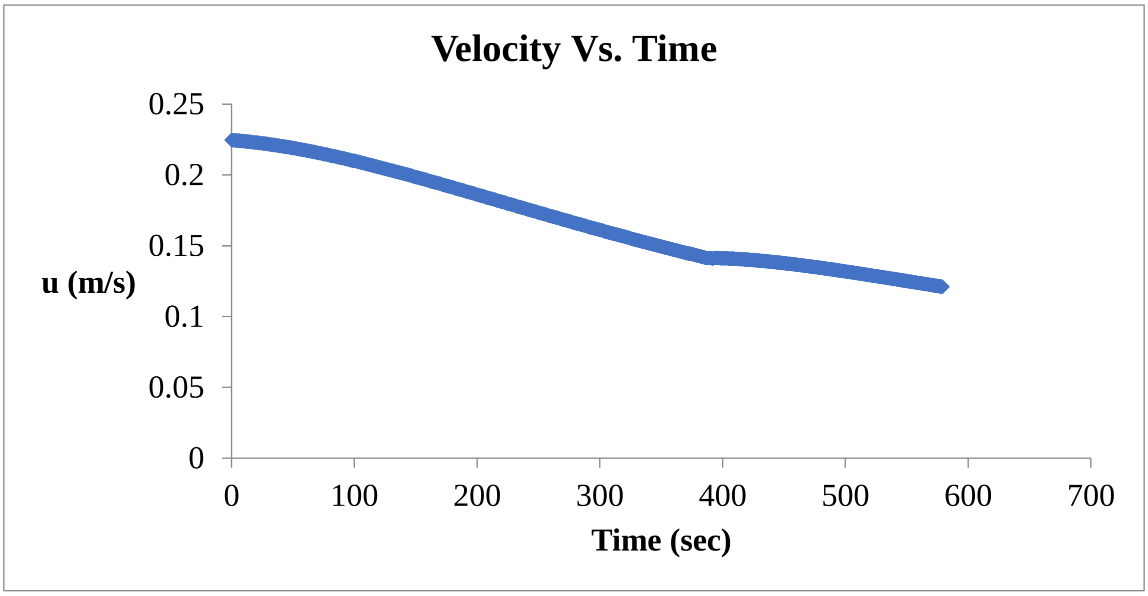

Figure 6: Variation in heat transfer coefficient inside the cooking vessel with time