Short Communication

Wall to fluid mass transfer in turbine agitated vessels

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Abstract

Heat and mass transfer operations in agitated vessels have so far been treated mainly in an empirical manner. In the present investigation an attempt has been made to propose equations for predicting wall to fluid mass transfer in turbine agitated vessels by considering boundary layer flow.

The model proposed is based on the established radial flow pattern for flat-bladed disc turbine. Experiments carried out show that the model predicts the concentration variation with time reasonably well.

Key words : Mass transfer, turbine agitated vessels.

1. Introduction

A knowledge of heat and mass transfer rates in agitated vessels is important for design purposes. Agitated vessels are extensively employed in chemical industry to increase heat transfer and mass transfer rates. So far, empirical relations have been employed for predicting heat and mass transfer rates in agitated vessels. The design of agitated vessels is based more on experience than on theory.

Dimensionless group correlations such as

$$N_{sh} = f(N_{Re}, N_{sc}) \tag{1}$$

have been employed to calculate heat and mass transfer coefficients.

In the present investigation an attempt has been made to propose an equation for obtaining solute concentration in liquid when mass transfer occurs from wall to fluid in agitated vessels. A flat-bladed turbine impeller with six vanes is employed in this study.

2. Experimental work

Apparatus

Experiments have been conducted in a flat bottomed cylindrical glass vessel. Salicylic acid (solid) solute-water (solvent) system is chosen for mass transfer studies. Salicylic acid is uniformly coated on the inner surface of the wall by melting the solid in small quantities and pouring on the surface and then allowing the material to solidify on the surface. This process is repeated until the thickness of the solid material is at least 2 mm. The surface is smoothened using blade and emery paper.

A turbine agitator with six flat blades is chosen for agitation. Four surface baffles have been provided at 90° interval to prevent vertex formation. A fractional H.P. motor (1/20 H.P.), fitted with a revolution counter, is used for driving the agitator. The glass vessel is placed in a thermostat to maintain isothermal conditions. The sensitivity of the thermostat is ± 0·1 °C. The experiments have been conducted at 29° C. A schematic diagram of the apparatus is presented in Fig. 1.

Experimental procedure

The thermostat is set to the desired temperature (29° C), and the vessel is placed in the thermostat. The agitator fitted with the motor is arranged in the vessel and adjusted such that it is at the centre.
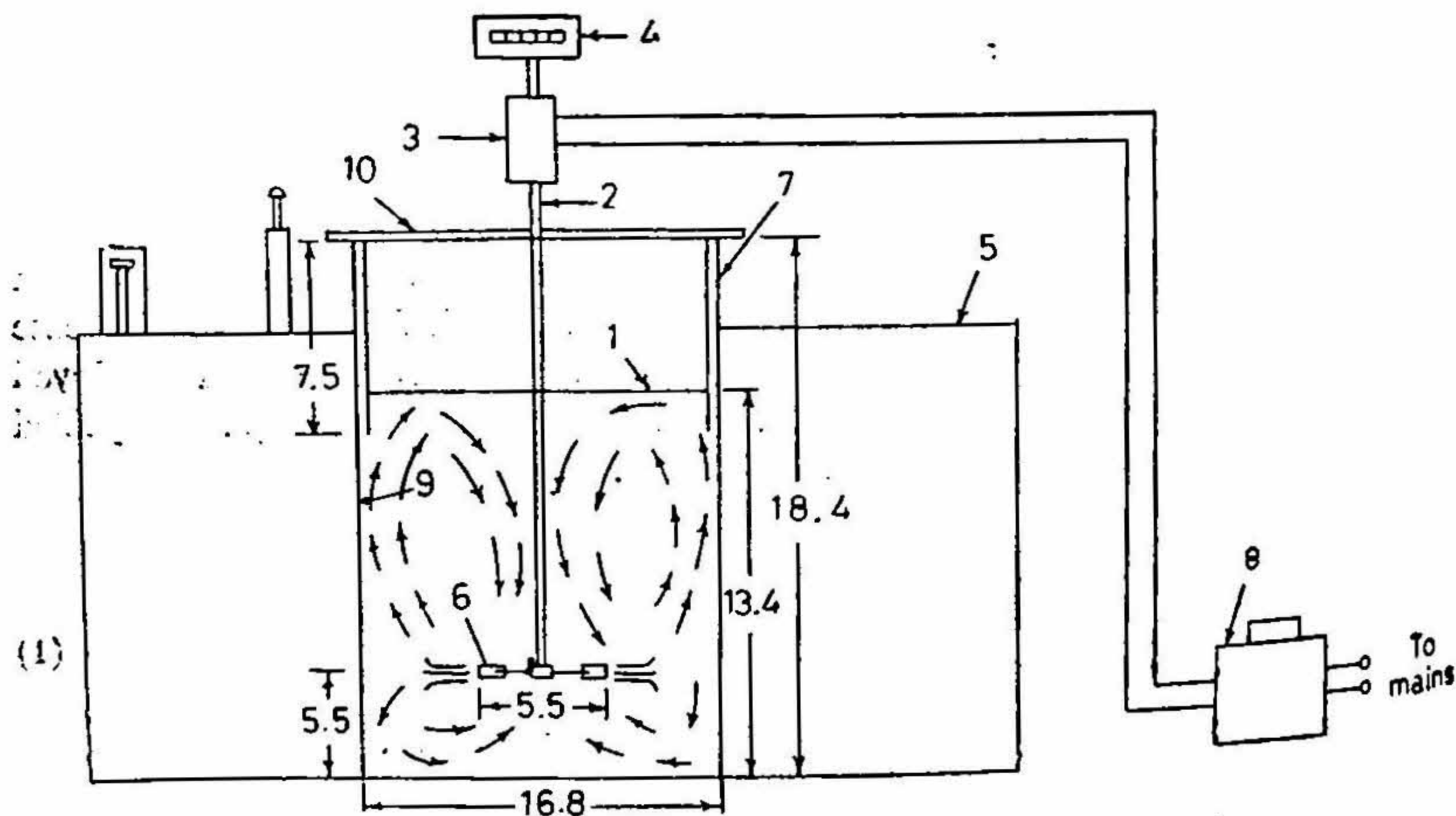

FIG. 1. Experimental set-up.

1. Liquid surface
2. Impeller shaft
3. Motor
4. Speed counter
5. Thermostat
6. Blade of the impeller
7. Surface baffle
8. Dimmerstat
9. Salicylic acid coating
10. Covering plate

The agitator is run at the required speed. The speed is adjusted using a dimmerstat. Using a hypodermic syringe a sample of 2 ml is taken as soon as the liquid is introduced and this gives the initial concentration. Similarly 2 ml samples have been collected at 5 minute intervals until the liquid reaches nearly saturation concentration. It has been observed that in two hours time the liquid attains nearly saturation concentration. The sample is filtered into the sampling tubes while collecting the sample in order to avoid any inaccuracy due to the possible presence of solid particles.

It is assumed that the properties of the solution like density, viscosity are those of pure solvent at the temperature, at which the experiments have been conducted.

Density of solution $= 0.99598$ gm/cm^3

Viscosity of solution $= 0.00818$ gm/cm. sec.

Saturation concentration of
salicylic acid in water at 29° C $= 0.00264$ gm/cm^3

Diffusivity of salicylic acid
in water at 290 °C $= 1.09 (10^{-5})$ cm²/sec.

3. Development of the model

Equations for unsteady state mass transfer are derived, considering the flow pattern of liquid in the vessel. The flow pattern in the case of a turbine agitated vessel is described below.

The impeller drives the liquid radially against the wall, where the stream divides into two portions. One portion flows downward along the wall to the bottom of the vessel and back to the impeller. The other portion flows towards the surface of the liquid and back to the impeller. The flow pattern would be as shown in Fig. 1.

At fairly high speeds of the impeller[5], the concentration of the liquid bulk may be considered to be uniform. Thus the total drop in concentration occurs within a layer near the wall.

The liquid in this layer will be at a higher concentration than the liquid bulk in the vessel. This liquid layer contributes to the mass transfer, to a considerable extent by mixing with the bulk of the liquid at the top and bottom of the vessel, in addition to the convective mass transfer occurring across the boundary layer.

The mass transfer due to the boundary layer mixing is predicted with the help of the solutions of the momentum boundary layer and concentration boundary layer equations. Thus, in this study, the mass transfer in the agitated vessel is considered to take place due to two mechanisms, (1) due to the transfer of mass across the boundary layer and (2) due to boundary layer mixing.

Mass transfer due to convection

In an agitated vessel coated with a soluble organic solid on the inner surface of the vessel, the concentration at liquid-solid interface is the saturation concentration. If 'C' is the concentration of the liquid bulk at any instant and 'C$_s$' is the saturation concentration, then the concentration gradient is $(C_s - C)$.

If 'A_1' and 'A_2' are areas of the vessel wall above and below the plane of the impeller, k_1 and k_2, are mass transfer coefficients respectively for transfer across the layers for the areas considered above, then the mass transfer across the boundary layer due to concentration gradient $(C_s - C)$, is given by

$$(NT)_c = A_1 k_1 (C_s - C) + A_2 k_2 (C_s - C) \tag{2}$$

For simplicity in mathematical analysis the upper and lower portions of the vessel are considered to be two flat plates with liquid flowing at zero incidence. Hence, the equations applicable for flat plate have been used for the calculation of average mass transfer coefficient.

The equation for the coefficient of mass transfer across the laminar boundary layer over a flat plate is given by :

$$KL/D = 0 \cdot 664 \ (N_{Sc})^{0 \cdot 33} \ (N_{Re})^{0 \cdot 5} \tag{3}$$

Mass transfer due to boundary layer mixing

For the calculation of this quantity, knowledge of volume rate of flow and the average concentration of the liquid in the boundary layer is essential. It is assumed that the boundary layer developed is in the laminar region. Calculation of the volume rate of flow of the liquid in the boundary layer requires the average thickness and velocity of the liquid of the boundary layer. Similarly, the computation of average boundary layer liquid concentration requires the knowledge of velocity profile and concentration profile within the layer.

The boundary layer thickness increases in axial direction along the wall both towards the top and bottom of the vessel from the stagnation point. At the top and the bottom of the vessel the boundary layer mixes with the bulk of liquid.

Solutions of laminar boundary layer equations given by Eckert and Drake[2] are used to obtain the average velocity and concentration of the liquid in the boundary layer.

The boundary layer equation for a flat plate for constant pressure is given by

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} \tag{4}$$

and the continuity equation is

$$\partial u/\partial x + \partial u/\partial y = 0 \tag{5}$$

Using the method of solution suggested by Von Karman, the velocity profile in the boundary layer[2] is obtained as

$$\frac{u}{U_s} = \frac{3}{2}\frac{y}{\delta} - \frac{1}{2}\left(\frac{y}{\delta}\right)^3 \tag{6}$$

where

$$\delta = \frac{4\cdot 64}{(N_{Re})^{0.5}}L \tag{7}$$

Similarly the concentration profile in the boundary layer is given by

$$\frac{C_b - C_s}{C - C_s} = \frac{3}{2}\left(\frac{y}{\delta_m}\right) - \frac{1}{2}\left(\frac{y}{\delta_m}\right)^3 \tag{8}$$

The velocity of the liquid at different locations in the vessel varies from 0·4 to 0·25 times the tip velocity[3]. The main stream velocity is assumed to be equal to the average of the two values. Hence the main stream velocity is taken as 0·325 times the tip velocity of the impeller.

In the case of mass transfer, the proposed drop in concentration occurs in the concentration boundary layer of thickness 'δ_m'. Hence, it is necessary to find the average concentration and average velocity within this thickness of the boundary layer. Therefore, the corresponding equations are integrated from zero to 'δ_m', the concentration boundary layer thickness.

Thus,

$$\frac{u_{avg}}{U_s} = \frac{\int_0^{\delta_m}\left[\frac{3}{2}\frac{y}{\delta} - \frac{1}{2}(y/\delta)^3\right]}{\int_0^{\delta_m} dy} \tag{9}$$

which gives

$$\frac{u_{avg}}{U_s} = \frac{3}{4}\varepsilon - \frac{1}{8}\varepsilon^3 \tag{10}$$

where

$$\varepsilon = \delta_m/\delta \tag{11}$$

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Similarly

$$\frac{\bar{C}_b - C_s}{C - C_s} = \frac{\int_0^{\delta_m} \left[\frac{3}{2}(y/\partial_m) - \frac{1}{2}(y/\partial_m)^3\right] dy}{\int_0^{\delta_m} dy} \tag{12}$$

or

$$\bar{C}_b = 5/8(C - C_s) + C_s \tag{13}$$

where '∂_m' is related to '∂' by[4]

$$\partial_m/\partial = 1/1\cdot026(1/N_{Sc})^{0\cdot33} \tag{14}$$

The area of flow is then given by

$$A' = 2\pi r \partial_m \tag{15}$$

where 'r' is radius of the vessel.

A' is the area of flow of the boundary layer at a point where the mass transfer boundary layer thickness is ∂_m. To evaluate the areas of flow at the top and bottom of the vessel the corresponding values of ∂_m are to be used in equation (15).

If A_1' and A_2' are the areas of flow for the boundary layer mixing for the top and bottom layers the equation for unsteady state mass transfer can be written as:

$$V(dC/dt) = A_1 k_1(C_s - C) = A_2 k_2 (C_s - C) + A_1' u_{avg} (\bar{C}_b - C)$$
$$+ A_2' u_{avg} (\bar{C}_b - C) \tag{16}$$

Equation (16) can be written, after simplification as

$$dC/dt = (C_s - C) M \tag{17}$$

where

$$M = k_1 A_1 + k_2 A_2 + (3/8) u_{avg} (A_1' + A_2') \tag{18}$$

M is constant for a given speed of the impeller.

Solving equation (17) with initial condition at $t = 0$, $C = C_0$ we obtain

$$. C = e^{-Mt}. (C_0 - C_s) + C_s \tag{19}$$

Thus with the help of this equation, it is possible to predict the concentration of liquid in the vessel at any time for any impeller speed within the range mentioned by Strek[5].

4. Results and discussion

Plots of concentration *versus* time have been presented in Figs. 2-6 both from theoretical calculations and experimental data. Theoretical calculations are made for the cases considering both convection and boundary layer mixing together and when convection mechanism alone is considered.

From the results of the few experiments carried out, it is seen that the experimental values are comparable at high impeller speeds to the theoretical values, when considering both convection and boundary layer mixing. However, further detailed experimental work is necessary in order to improve the theoretical approach.

5. Conclusions

A model has been proposed for estimating the solute concentration in liquid when mass transfer occurs from wall to liquid in agitated vessels by considering boundary layer mixing, in addition to convection. The results of the experiments show comparable values to those estimated by this model, especially at high impeller speeds.
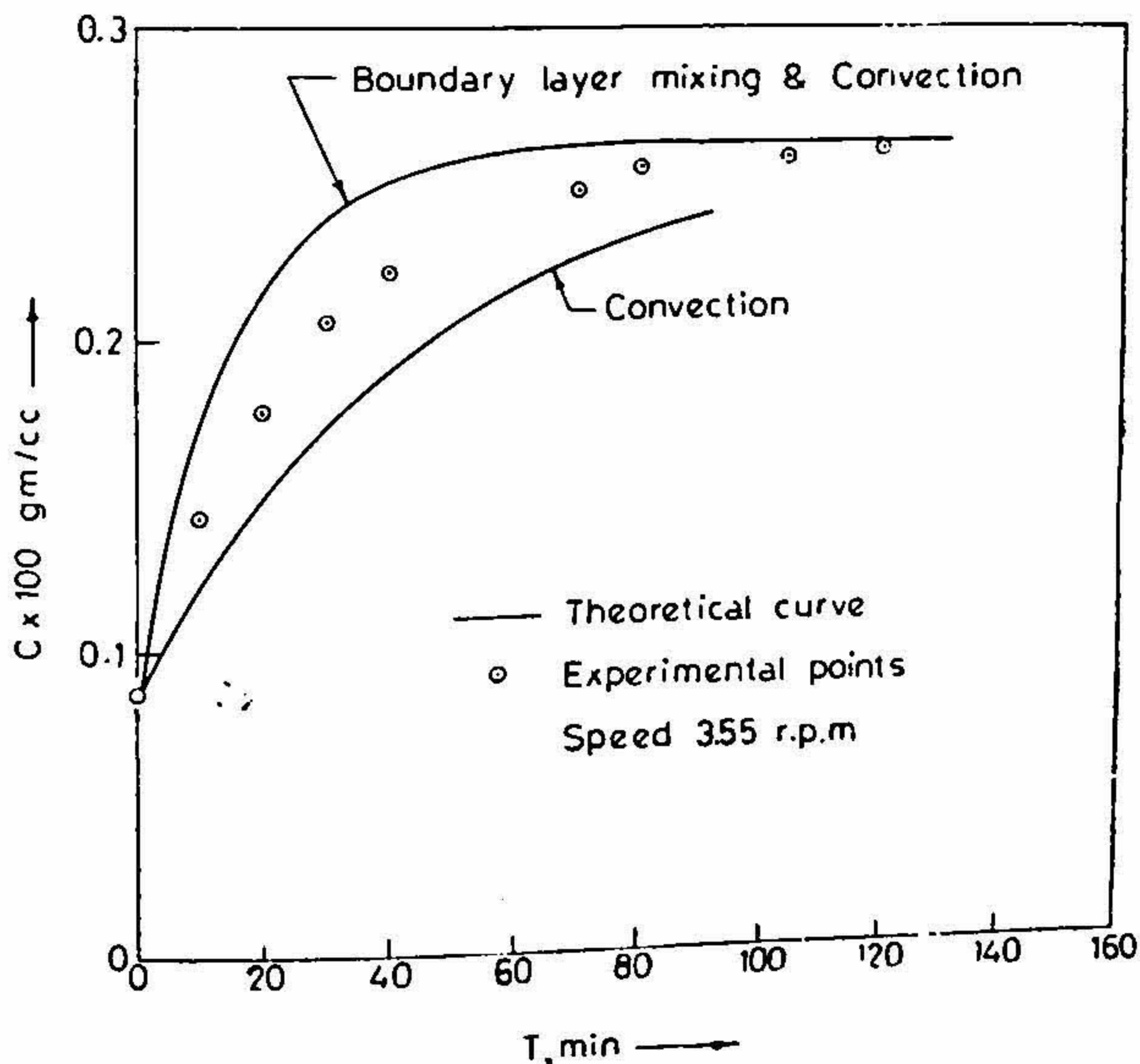
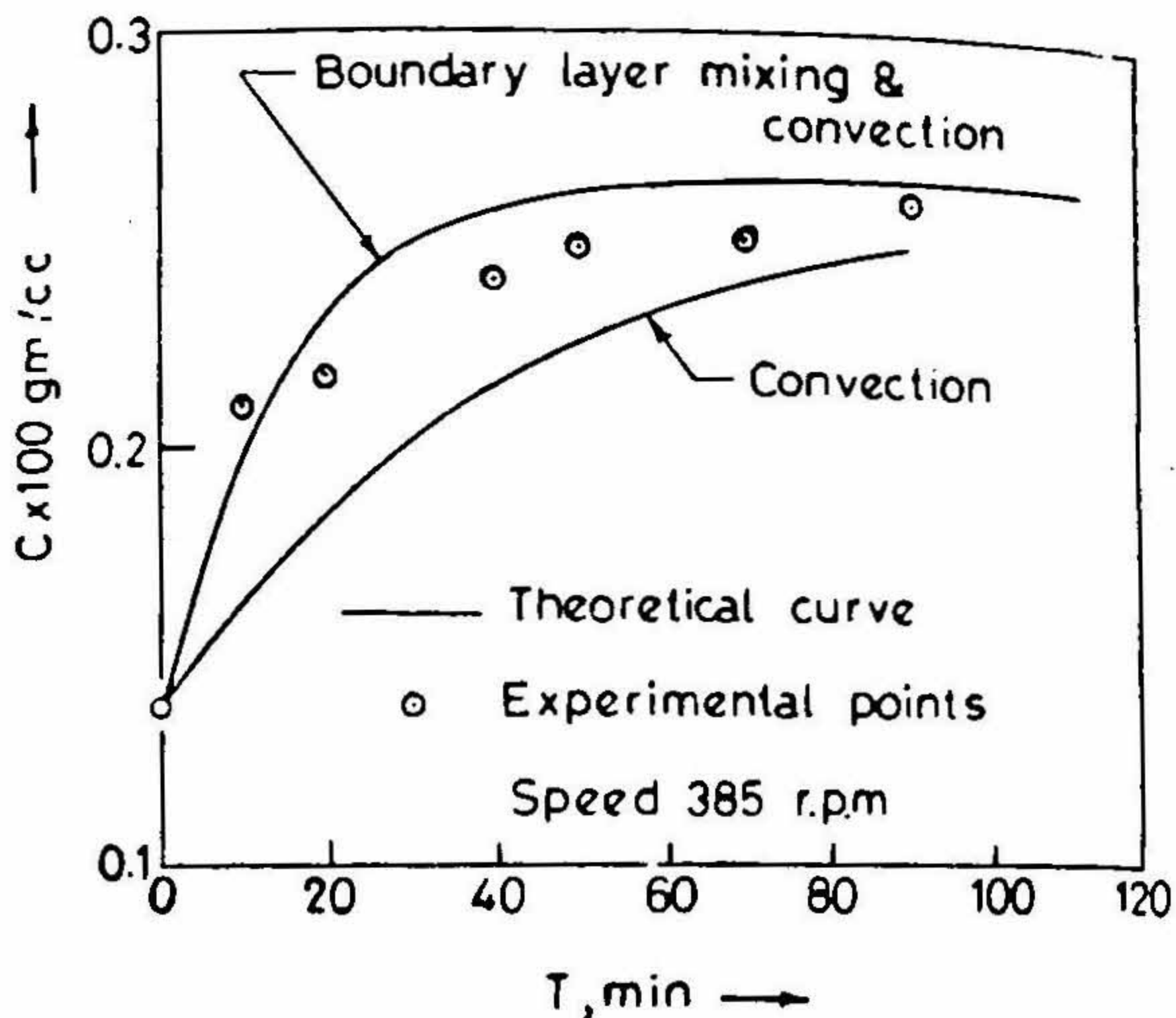Fio. 2. Change in concentration of salicylic acid with time.

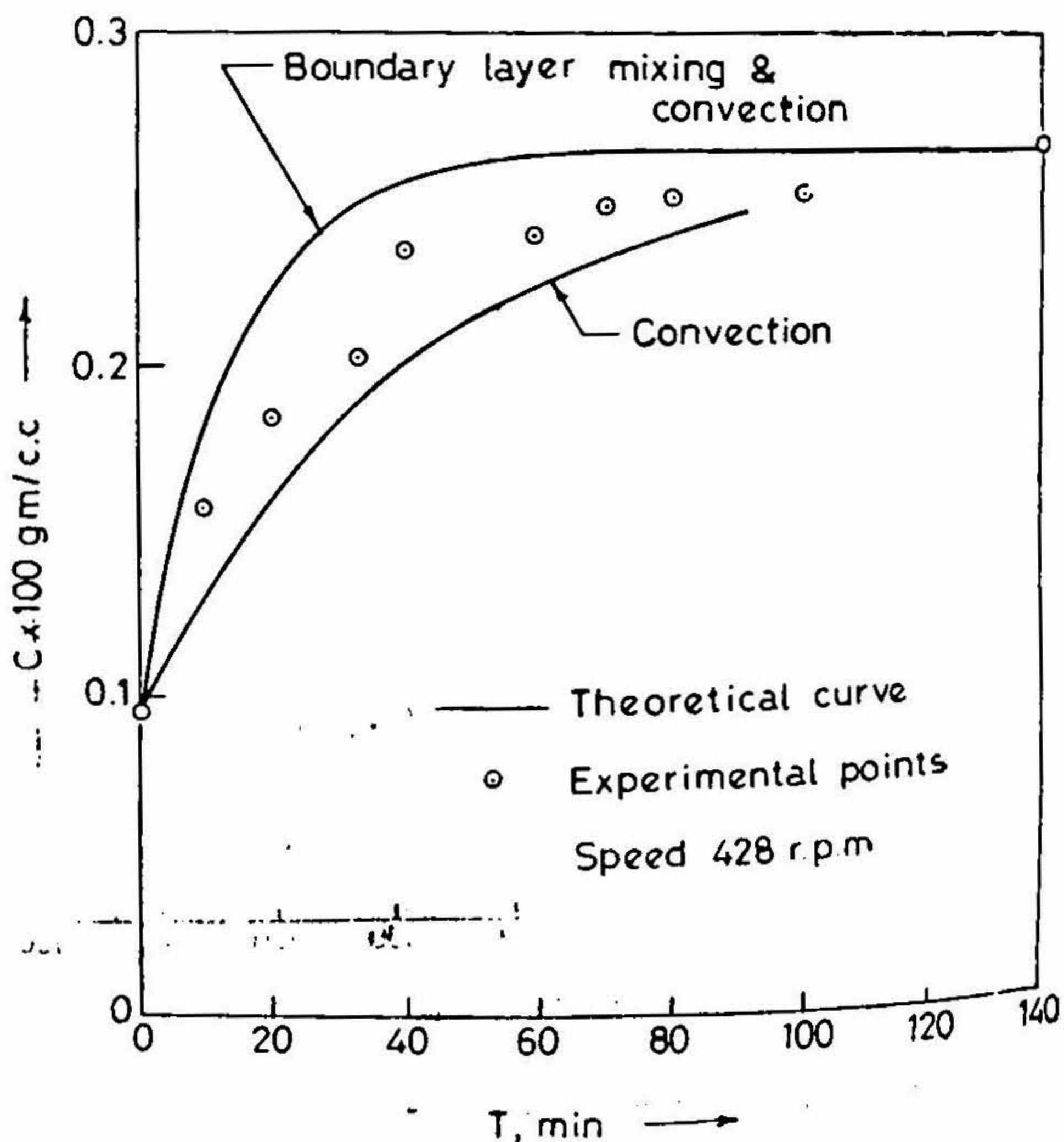FIG. 3. Change in concentration of salicylic acid with time.

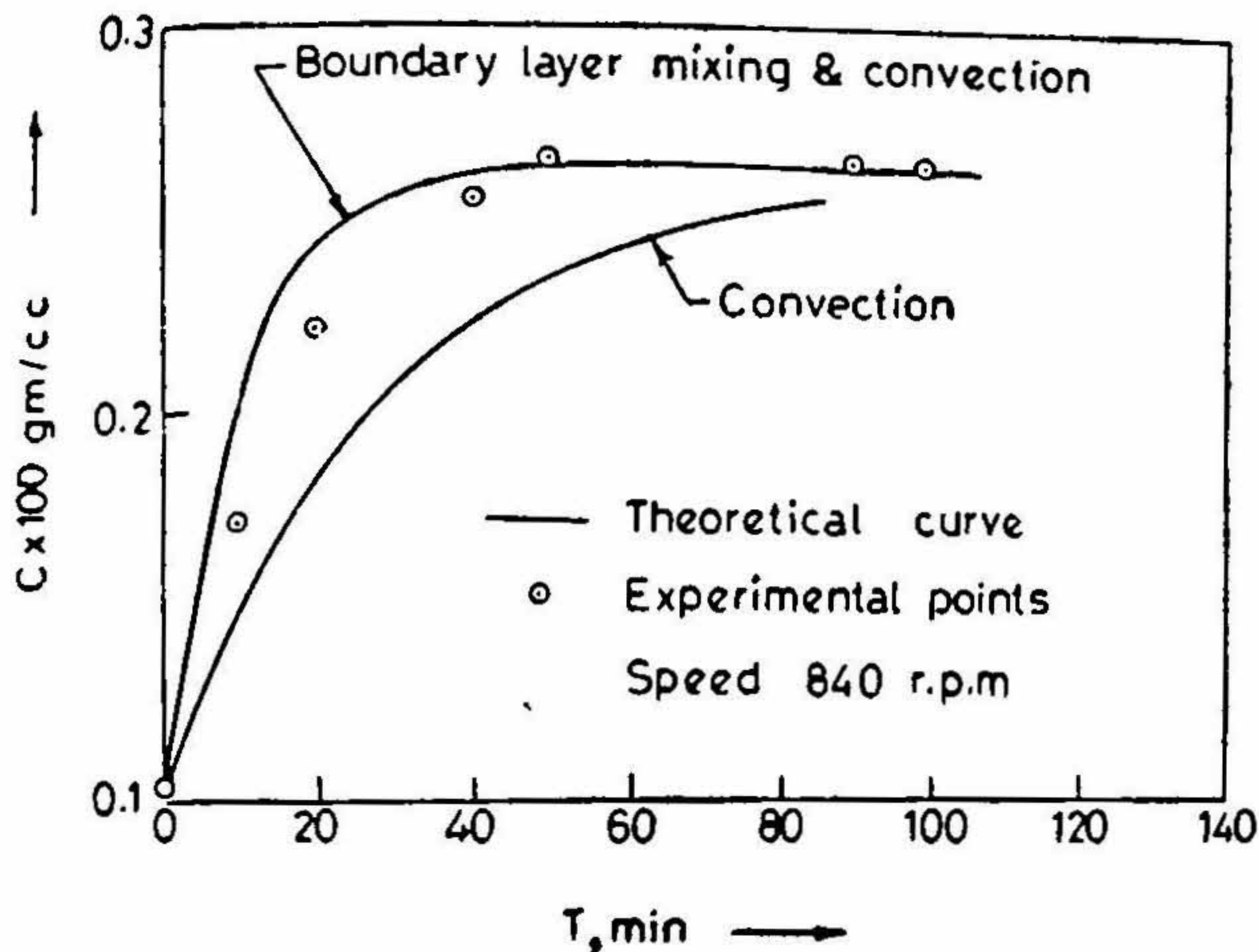FIG. 4. Change in concentration of salicylic acid with time.

FIG. 5. Change in concentration of salicylic acid with time.

Notation

A_1 Area of the surface of the wall of the vessel above the level of the impeller (cm²)

A_2 Area of the surface of the wall of the vessel below the level of the impeller (cm²)

A_1' Area of flow of boundary layer at the top of the vessel (cm²)

A_2' Area of flow of boundary layer at the bottom of the vessel (cm²)

C Concentration of solution at any time t (gm/cc)

$\bar{C}_b$ Average boundary layer liquid concentration (gm/cc)

C_0 Initial concentration (gm/cc)

C_s Saturation concentration (gm/cc)

d Diameter of the impeller (cm)

D Diffusivity (cm²/sec)

K Mass transfer coefficient (cm/sec)

k_1 Mass transfer coefficient valid for surface of the vessel above the level of the impeller (cm/sec)
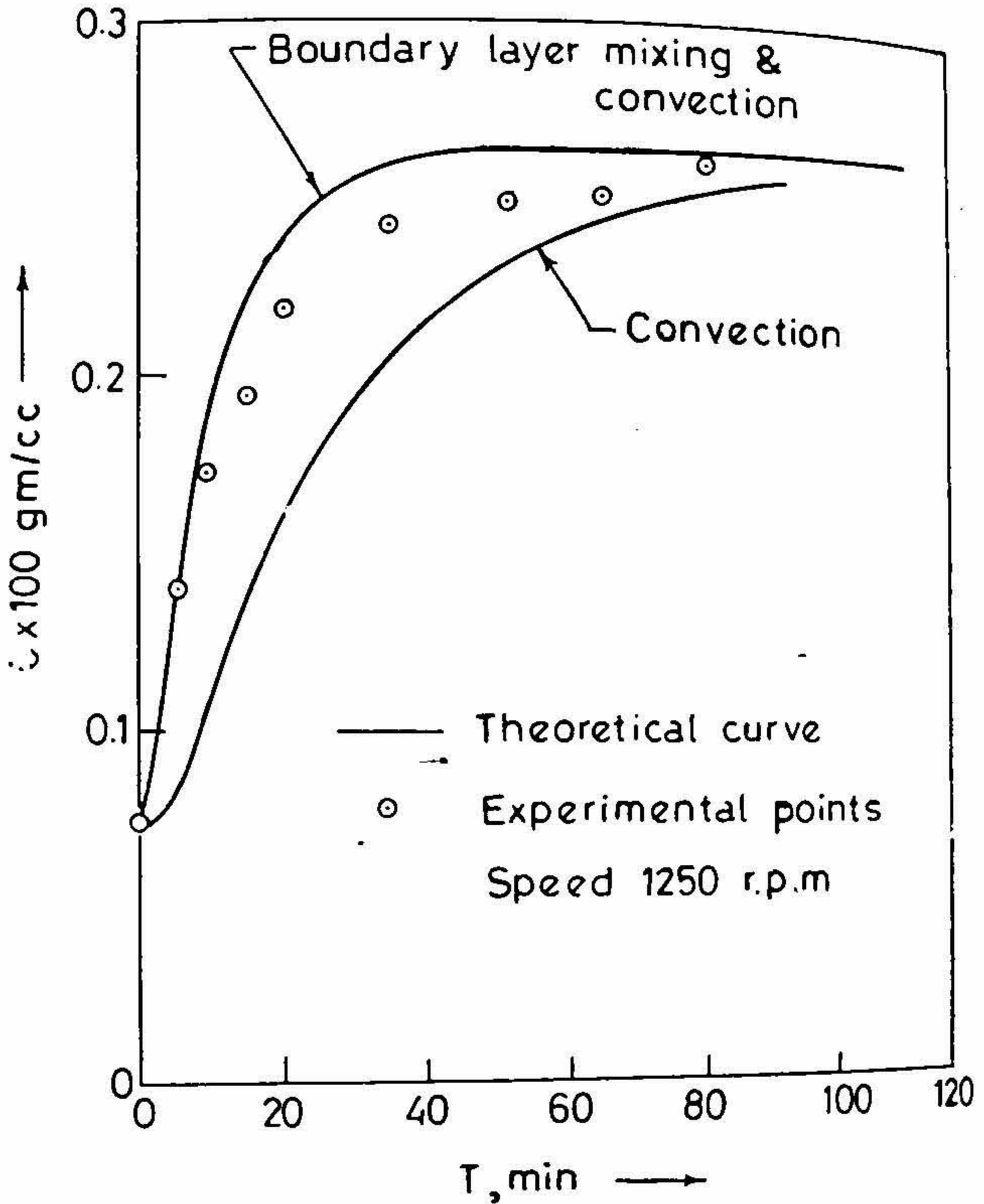
FIG. 5. Change in Concentration of salicylic acid with time.

k_2 Mass transfer coefficient valid for the surface of the vessel below the level of the impeller (cm/sec)

L_1 Length of the vessel above the impeller (cm)

L_2 Length of the vessel below the impeller (cm)

N_{sh} Sherwood number (KL/D)

N_{Re} ·   Reynolds number $(U_s L \rho)/\mu$

N_{sc} Schmidt number $(\mu/\rho D)$

N_{Pr} Prandtl number $(C_s \mu/k)$

$(NT)_c$ Mass transfer rate across the boundary layer

t Time (sec)

U_s Main stream velocity (cm/sec)

u_{ms} Average velocity in the boundary layer (cm/sec)

V Volume of the vessel (cm^3)

x Distance in the direction of flow (cm)

y Distance from the surface in the direction perpendicular to the surface (cm)

Greek symbols

μ Viscosity of water (gm/cm sec)

ρ Density of water (gm/cc)

δ Hydrodynamic boundary layer thickness (cm)

ε Ratio of hydrodynamic and concentration boundary layer thickness

δ_m The concentration boundary layer thickness

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