

CHAPTER 4

EXPERIMENTS AND ANALYSIS

4.1 EXPERIMENTAL SETUP

The details pertaining to experimental work carried out in the laboratory scale SO₂ emission control experimental system are described in this section. The functional diagram and photographic view of the experimental set up are shown in Figures 4.1 and 4.2. It comprises a mixing tank with 15 litres capacity, acid tank of 5 litres capacity, and water tank with 10 litres capacity. Pure calibrated SO₂ gas of 100% from the SO₂ gas cylinder and air from the compressor are fed into the mixing chamber. In the mixing chamber, SO₂ gas is mixed with compressor air to maintain the concentration of SO₂ at the inlet at 5000 ppm. SO₂ gas flow rate is maintained between (0-0.5 lph) and mixed with air at a flow rate of 40m³/hr. From the mixing chamber, the mixed gas enters the bottom of the packed column through air dryer. The air dryer consists of a heater surrounding the inlet and outlet air tubes and it is used to suppress the moisture content in the air. Check valve is connected between SO₂ gas cylinder and mixing chamber which is a non return valve. In addition to that, the rotameters (R₁, R₂, R₃, R₄ and R₅) are employed to measure the flow rate of liquid and gas.

Acid tank is filled with H₂O₂ with the required concentration and it is pumped into the recirculation tank through the peristaltic pump. Recirculation tank is initially filled with sulphuric acid with required concentration and it is mixed with externally added H₂O₂.

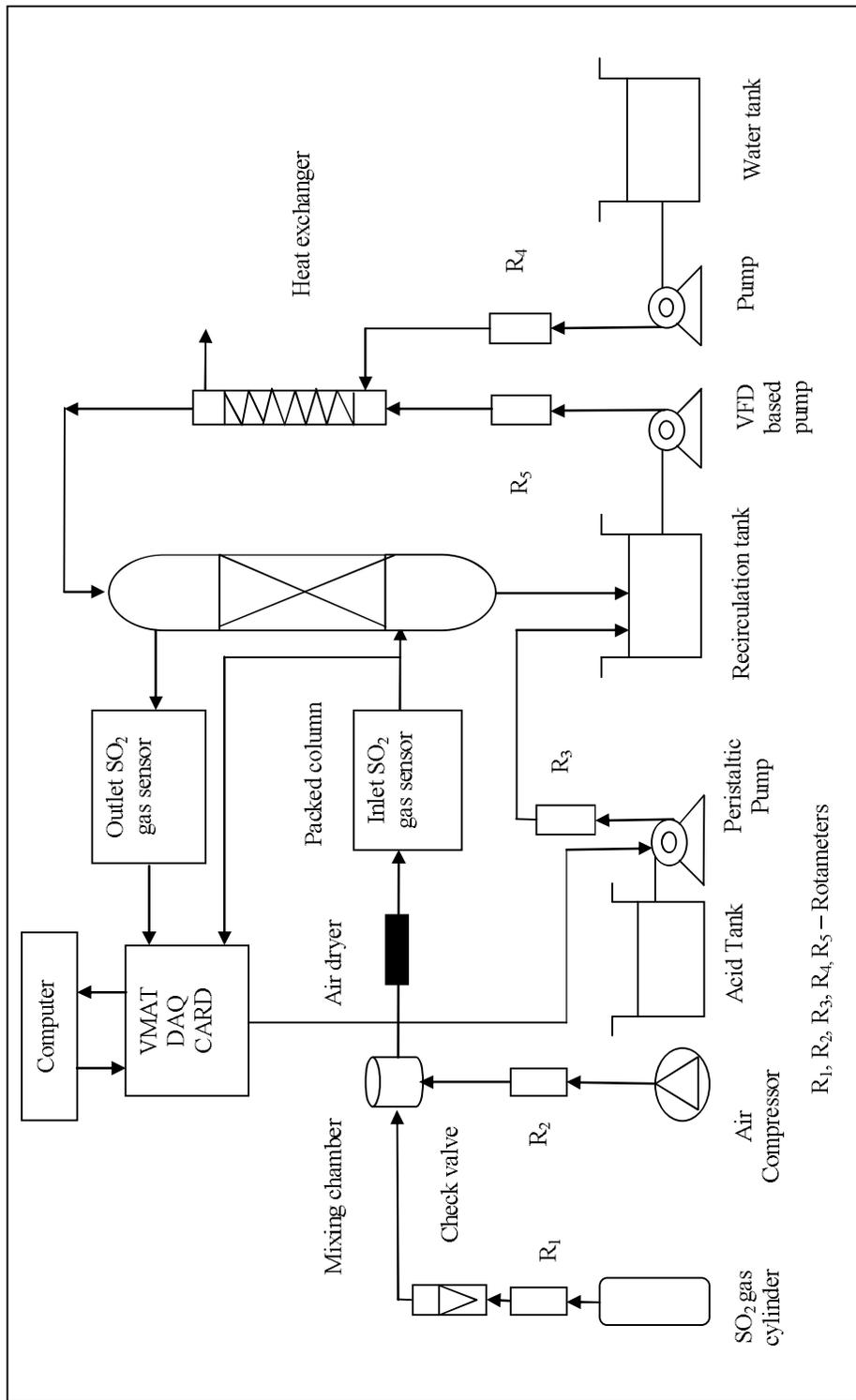


Figure 4.1 Functional diagram of the experimental set up

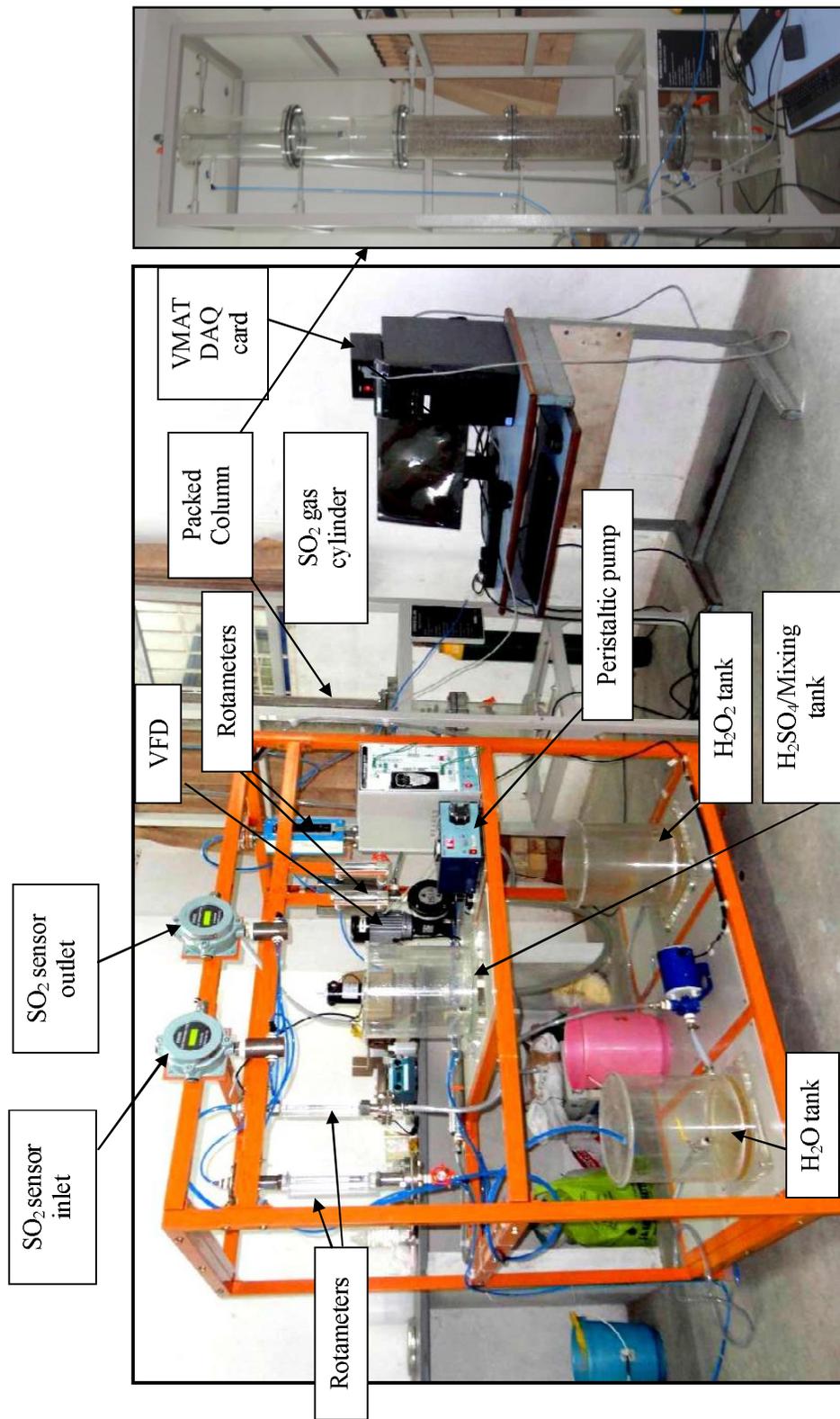


Figure 4.2 Photographic view of the experimental set up

The solution in the recirculation tank is pumped to the counter current section (top) of the packed column with the flow rate of 150 lph. In the packed column, the liquid enters at the top and mixed gas enters at the co-current section (bottom) of the packed column and both are blended together in the packed area. Absorption with chemical reaction takes place in the packed column and as a result, SO₂ from gas phase is dissolved into the liquid phase by making a chemical reaction between them. Based on the mass transfer occurring between gas and the mixed solution, SO₂ gets absorbed into the liquid.

The untreated gas exits through the outlet of the packed column. The concentration of SO₂ at the inlet and outlet of the packed column is measured by two SO₂ gas sensors. The output of the inlet and outlet SO₂ sensors are converted into current signal (4–20 mA) by means of a transmitter powered by a 24 V DC power supply. The SO₂ emission control system is interfaced with the PC through a specially designed microcontroller based VDPID-03 unit as shown in Figure 4.3. This unit comprises multifunction, high-speed Analog and Digital Converter (ADC) interface board with 8 channel ADC and 2 channel DAC facilities which are used to send the control signal to the peristaltic pump. They help in implementing real time control algorithm written in MATLAB/SIMULINK platform. The sensor readings are recorded in a computer with 0.1 sec sampling time interval.

The current signals from the inlet and outlet SO₂ sensors are connected to two channels of VDPID-03 card and converted into a voltage signal (0 – 5V) by using current to voltage converter. The analog voltage signals are converted into digital signal by ADC. The digital signal from VDPID-03 unit is fed as the input to the PC based controller. In PC, the readings taken from inlet SO₂ gas sensor is maintained as inlet SO₂ concentration and the readings taken from outlet SO₂ gas is maintained as the measurement variable.

The output voltage signal (0 – 5 V) from the PC based controller is in the form of digital signal and it is converted into an analog signal by DAC. Then the voltage signal is converted as a current signal (4 – 20 mA). This current signal is directed to actuate the peristaltic pump which acts as a final control element. The output current signal from VDPID-03 unit is given to the peristaltic pump and converted as speed (0-100 rpm). Speed variation of the peristaltic pump is obtained by the precise PWM based DC motor drive. This drive is used for driving the peristaltic pump based on the current signal. Based on the SO₂ concentration in the untreated gas, the flow rate of the H₂O₂ is manipulated through the peristaltic pump. A detailed description of the instruments used in the SO₂ emission control experimental set up is explained in the subsequent sections. The design details of the experimental set up are given in Appendix 1.

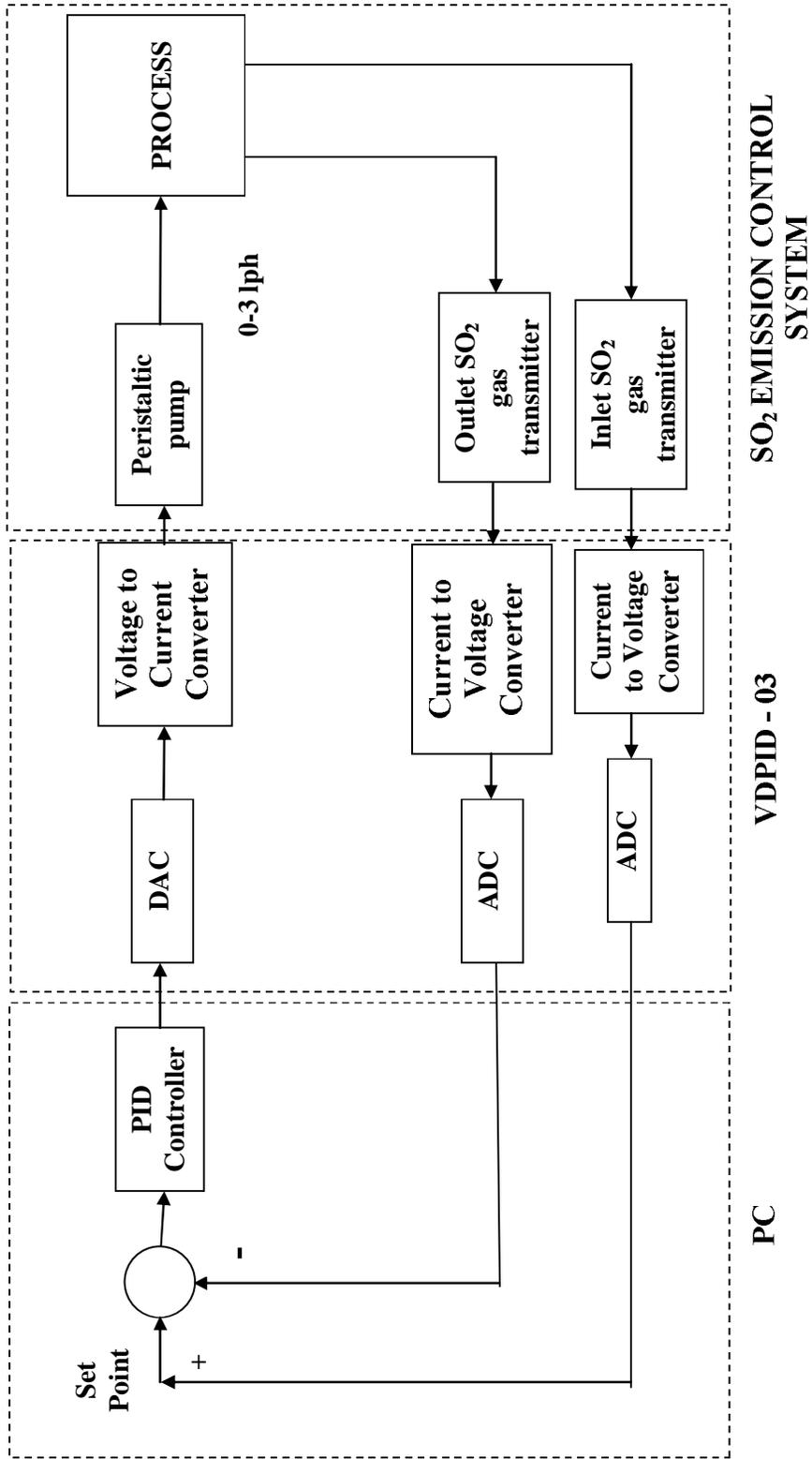


Figure 4.3 Interfacing diagram

4.2 INSTRUMENTATION AND MEASUREMENTS

The following details provide the hardware elements involved in the measurement and control.

4.2.1 SO₂ Gas Sensor with Transmitter

SO₂ gas sensor with a transmitter is fixed at the inlet and outlet parts of the packed column used for measuring SO₂ concentration in the air stream and it transmits equivalent electrical signal to the computer. The photographic view of the SO₂ gas sensor with the transmitter is shown in Figure 4.4.



Figure 4.4 SO₂ gas sensor with transmitter

The SO₂ gas sensor consists of two parts, namely process electrode and a controller. The process electrode consists of an anode, a cathode and an electrolyte. When the components of the process electrode are subjected to gas, they allow diffusion into the process electrode, make chemical reaction and generate current. The diffusion in the process electrode depends on the concentration of gas that enters into the sensor. The current generated is proportional to the rate of the consumption of the SO₂ molecules in the process electrode.

The second part is the controller which converts the measured electrical signal into equivalent SO_2 concentration. The measurement range for the SO_2 gas sensor is 0-5000 ppm for the corresponding current range of 4-20 mA. A display unit in the transmitter shows the concentration of SO_2 at the inlet and outlet terminal.

The SO_2 gas sensor is calibrated with the standard SO_2 calibration mixture (5000 ppm SO_2 gas) filled in a small canister and it is fed into the SO_2 gas sensor to ensure the reproducibility of the results and standards. The specifications of SO_2 gas sensor is given in Table A1.2.

4.2.2 Variable Frequency Drive

An induction motor with Variable Frequency Drive (VFD) is connected at the liquid inlet of the packed column used for pumping the liquid into the packed column at various flow rates as shown in Figure 4.5. To achieve variations in the flow rate, VFD is used to control the induction motor speed and torque by varying motor input frequency and voltage.

The VFD controller is a solid state power electronic device consisting of three distinct sub-systems, namely rectifier bridge converter, Direct Current (DC) link, and inverter. Voltage Source Inverter (VSI) drives are AC-AC drives which are used to convert AC line input to AC inverter output. In a VSI drive, the DC link consists of a capacitor which smooths out the converter's DC output ripple and provides a stiff input to the inverter. This filtered DC voltage is converted to sinusoidal AC output voltage using the inverter.

The operator interface section available in the VFD drive provides the means for an operator to start and stop the motor and adjust the speed. The operator interface includes an alphanumeric display showing frequency and

voltage at which the drive is operating. An operator interface keypad and a display unit are provided on the front of the VFD controller as shown in the Figure 4.5. A serial communication port is used to configure, adjust, monitor and control the VFD by a computer.



Figure 4.5 Variable frequency drive with induction motor

4.2.3 Peristaltic Pump

The peristaltic pump RH-P120VS shown in Figure 4.6 is a single channel positive displacement pump used where an accurate flow control is essential for the variety of fluids. The fluid is contained within a flexible tube fitted inside a circular pump casing and a rotor with a number of rollers attached to the external circumference of the rotor compresses the flexible tube. As the rotor rotates, the part of the tube under compression is pinched and it forces the fluid to move through the tube. This pumping action is done by a roller cage driven by a permanent magnet DC motor. The rollers are made up of carbon filled nylon for trouble free operation. The speed of this pump is varied between 10-100 rpm and the corresponding flow rate is 0-3 lph.

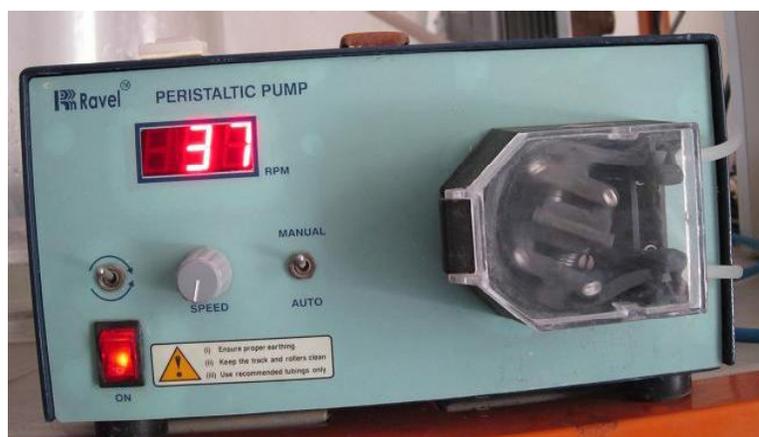


Figure 4.6 Peristaltic pump

The speed variation is obtained by means of an external 4-20 mA signal by a PWM based DC motor drive. According to the amplitude of current pulse, PWM drive produces ON/OFF control pulses to the permanent magnet DC motor. The speed of the roller changes according to the width of the pulse produced by the PWM drive and accordingly the flow rate of the liquid coming out of the flexible tube changes. The peristaltic pump is calibrated by measuring the acid flow rate of peristaltic pump for the different magnitude of DAQ output and it is depicted in Figure 4.7.

From the Figure 4.7, it can be seen that the “up scale” curve was obtained by continuously increasing the DAQ opening from 0% to 100%. On the other hand, the “down scale” curve was obtained by steadily decreasing the DAQ opening from 100% to 0%. This analysis ensures that the peristaltic pump responds in the same manner for both upscale and downscale readings. The graphic interpretation indicates that the peristaltic pump does not have very significant error. The detailed specifications of the peristaltic pump are given in Table A1.1.

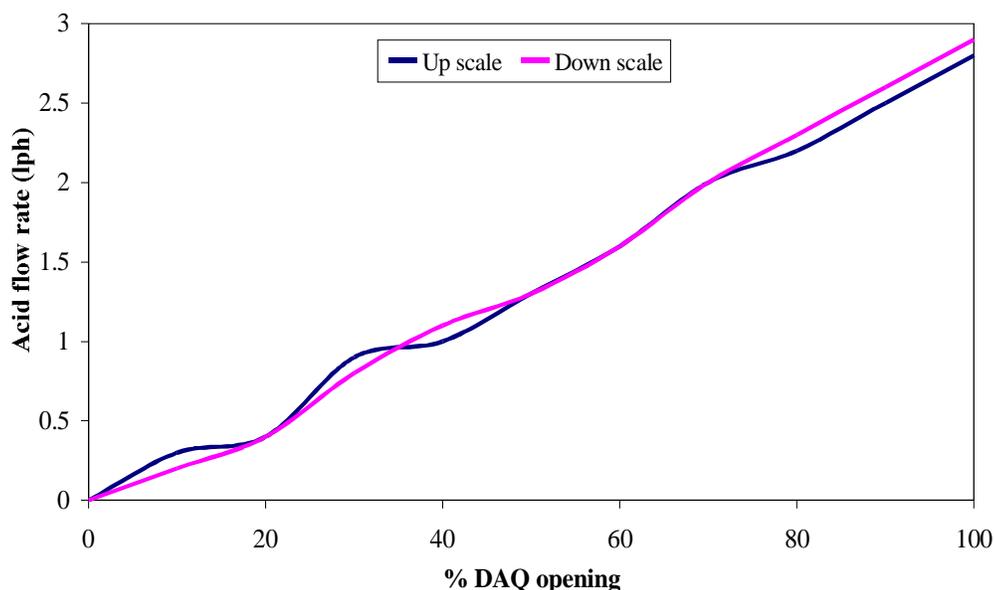


Figure 4.7 Calibration curve of peristaltic pump

4.2.4 VDPID-03 based Data Acquisition Card

A specially designed ADuC841 microcontroller based VDPID-03 unit is used for monitoring and controlling the SO₂ emission control process (M/s V-I Microsystems, Chennai, India). The functional diagram of VDPID-03 based data acquisition card is displayed in Figure 4.8.

The ADuC841 is a complete smart transducer front end, that integrates a high performance self-calibrating multi-channel ADC, a dual DAC, and an optimized single-cycle 20 MHz 8-bit MCU (8051 instruction set compatible) on a single chip. The ADuC841 is clocked directly from an external crystal up to 20 MHz. The microcontroller is an optimized 8052 core offering upto 20 MIPS peak performance. Three different memory options are available offering upto 62 KB of non-volatile Flash/EE program memory. In addition, 4 KB of non-volatile Flash/EE data memory, 256 bytes RAM and 2 KB of extended RAM are also integrated on-chip. The parts also

incorporate additional analog functionality with two 12-bit DACs, power supply monitor and a band gap reference. On-chip digital peripherals include two 16-bit Σ - Δ DACs, a dual output 16-bit PWM, a watchdog timer, a time interval counter, three timers/counters and three serial I/O ports such as Serial Peripheral Interface (SPI), Inter Integrated Circuit (I²C) and Universal Asynchronous Receiver Transmitter (UART).

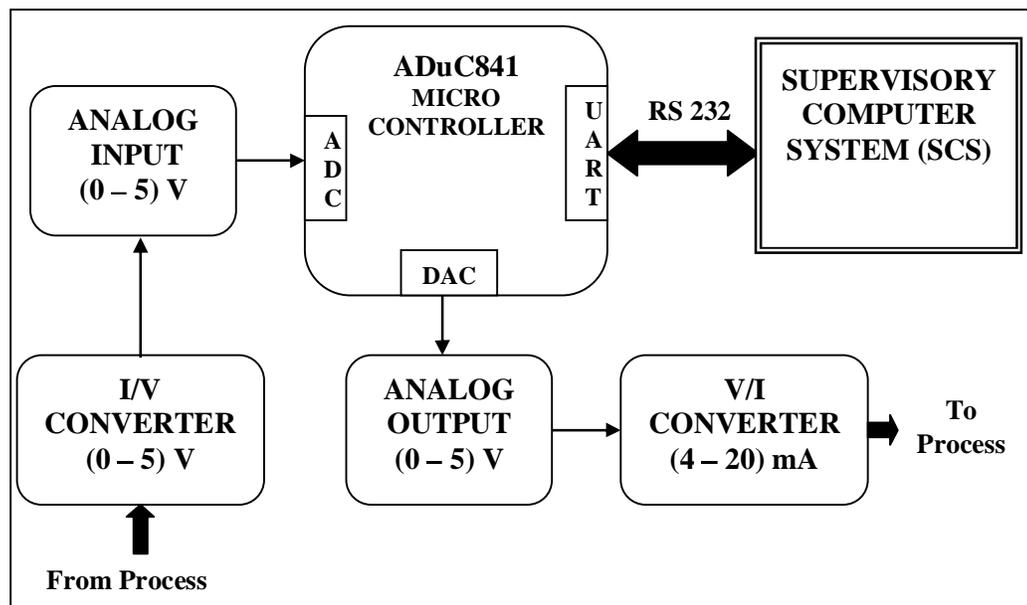


Figure 4.8 Functional diagram of VDPID-03 card

VDPID-03 unit is interfaced with PC through RS 232 network interface. The PC uses MATLAB/SIMULINK software as a tool to handle all the activities of the SO₂ emission control system such as process monitoring and data interpretation. The card is also MATLAB based and operates within the same PC platform (Windows NT/2000/XP). The main function of this card is to allow real time communication between the PC and measuring instruments used in the SO₂ emission control system. The main advantage of the card is that the users have the flexibility to develop their own GUI. The developed GUI is used to control and monitor the status of the SO₂ emission control system.

The layout of the developed GUI used for the experimental work on the laboratory scale SO₂ emission control system is illustrated in Figure 4.9. In this Figure 4.9, the two query instrument blocks configure and open an interface to an instrument, initialize the instrument and queries the instrument for data. The configuration and initialization happen at the start of the model execution. The block queries the instrument for data during the model run time. This block acquires the data (actual SO₂ concentration value in the inlet and outlet gas stream) from the VDPID-03 interfacing unit in the range of 14095-19095, where 14095 corresponds to 0 ppm and 19095 corresponds to 5000 ppm. Here, 10000th position indicates the channel number of 12 bit 8 channel ADC section in VDPID-03 interfacing unit. The data from the query instrument are sent to ADC split block which is used to identify the channel number as well as to manipulate the data in terms of SO₂ concentration value. This bit of data is passed through the analog filter block which is used to remove the noisy data by using low pass filter.

The outlet SO₂ concentration value from the analog filter design block compares with the desired set point SO₂ concentration value and generates the error signal to PID controller. The PID controller block and the fractional PID controller block are the two controller blocks used for analysis. These controllers are selected based on the selector switch. The output from PID controller is in SO₂ concentration value (0-5000) ppm which is subtracted by 5000. It manipulates as % value (0-100) using H₂O₂ Gain block and it is sent to the first channel of DAC split block. At the same time, the DAC split block receives the % H₂O₂ opening in the second channel. In DAC split, for channel identification, the data (0-100 %) is multiplied by 0.5 then added with 100 for the first channel (100-150) and 200 for the second channel (200-250). Accordingly, the program was written in ADuC841 microcontroller.

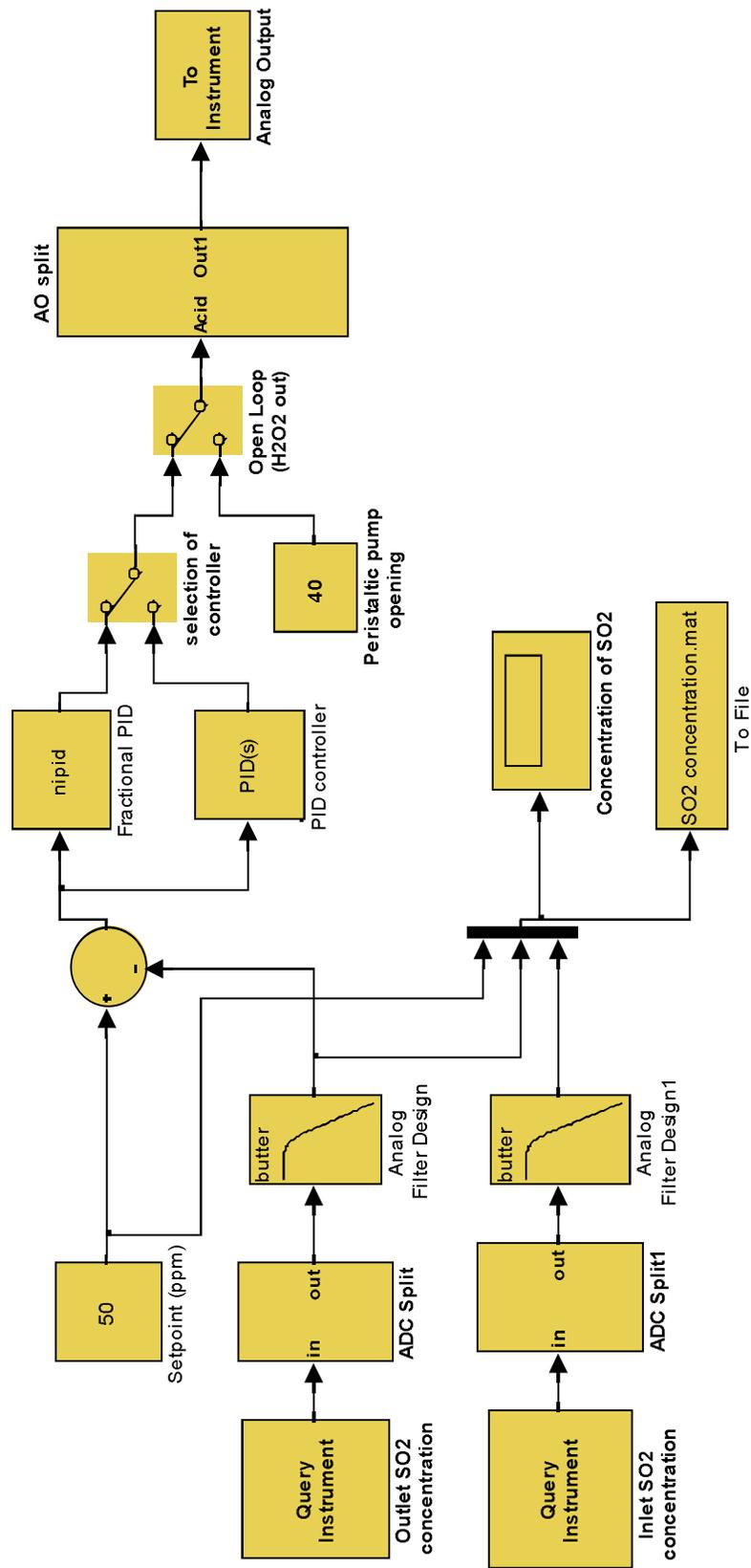


Figure 4.9 GUI for experimental work in MATLAB/SIMULINK platform

The data from DAC split are sent to the To Instrument block. The block configures and opens an interface to an instrument, initializes the instrument and sends the data to the instrument. The configuration and initialization happen at the start of the model execution. This block sends data to the instrument during the model run time. The block has no output ports and it has one input port. The input port of the To Instrument block sent the corresponding data to the SO₂ emission control system through VDPID-03 interfacing unit. The general specifications of the VDPID-03 card are given in Table A1.3.

4.3 EXPERIMENTAL ANALYSIS

The lab scale experimental set up is designed by considering mathematical modelling detailed in section 3.1 and CFD modelling in section 3.2 for achieving the maximum SO₂ removal efficiency. The parameters such as absorbent selection, packing material used are ensured by the experiments carried out in lab scale SO₂ experimental set up.

4.3.1 Effect of Absorbents on SO₂ Removal Efficiency

The effect of absorbents is analysed by conducting the experiments in the laboratory SO₂ emission control system continuously for 8 hours with each absorbent. Throughout the experiment, the temperature of the liquid is maintained as constant with the help of heat exchanger provided in the liquid loop. Hence the equilibrium between gas and liquid does not change with respect to temperature.

The effects of absorbents with respect to removal efficiency for different absorbents such as water, hydrogen peroxide (H₂O₂, 0.1 M), sulphuric acid (H₂SO₄, 0.01M), sodium hydroxide (NaOH, 0.1 M) and mixed hydrogen peroxide (0.1M) with sulphuric acid (0.01M) are recorded and

shown in Figure 4.10. Initially, inlet SO_2 concentration is maintained at 1000 ppm and the experimentation is carried out. Similarly, for the SO_2 inlet concentrations 2000 ppm, 3000 ppm, 4000 ppm and 5000 ppm, experiments are conducted for different absorbents. As shown in Figure 4.10, there are no much variations in the SO_2 removal efficiency pointed out for various inlet SO_2 concentrations. From the Figure 4.10, it is observed that the removal efficiency obtained from water absorbent is only 50 to 65% at various SO_2 inlet concentrations.

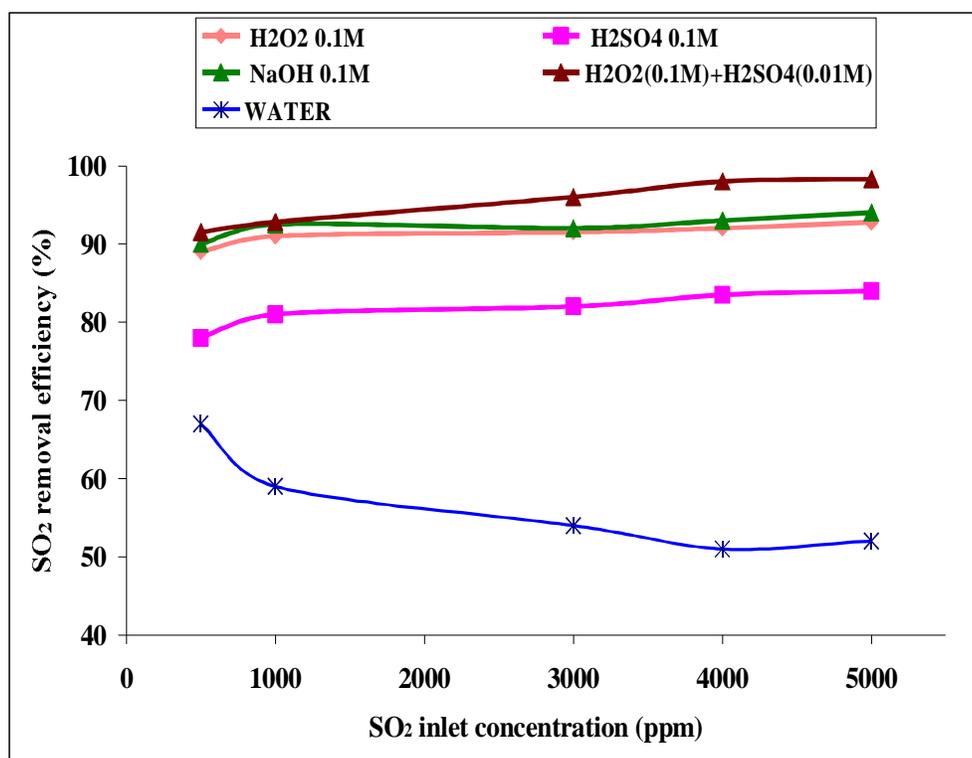


Figure 4.10 SO_2 removal efficiency for various absorbents



The reaction with SO_2 and H_2O is given in equation 4.1 is fast also it is considered as spontaneous. The reaction is not having the influence on

the mass transfer since the reaction times are in the order of 10^{-7} s, while mass transfer processes occur typically at 10^{-2} s. Furthermore, if SO_2 is not fully oxidized, there is a substantial vapour pressure of SO_2 above the absorbing solution. Though water is the mostly used absorbent in industrial practice, the fractional absorption occurred during continuous runs. Hence it is not considered in the present study.

During the reaction between SO_2 and sulphuric acid, the equilibrium between gas and liquid is maintained as constant but it is not so for increased sulphuric acid concentrations during continuous runs. Thus the removal efficiency is reduced during continuous absorption as compared to hydrogen peroxide absorption shown in Figure 4.10. When H_2SO_4 with 0.1M is used as an absorbent, SO_2 removal efficiency is 80% for all the cases of inlet SO_2 concentrations. During the continuous recirculation of H_2SO_4 , 0.1M of H_2SO_4 becomes more and more concentrated sulphuric acid. As per the results given by Colle et al (2004), the increase in concentration of H_2SO_4 decreases the absorption rate and hence pure H_2SO_4 is not considered for further analysis.

Similarly, during the experimental study using NaOH as an absorbent, the reaction kinetics and equilibrium between SO_2 with NaOH vary rapidly. Since NaOH solution does not produce resistance during the gas and liquid reaction, 0.1M NaOH produces around 90% for various inlet SO_2 concentrations and the graph shows that the removal efficiency gradient is more than hydrogen peroxide at different SO_2 inlet concentrations.

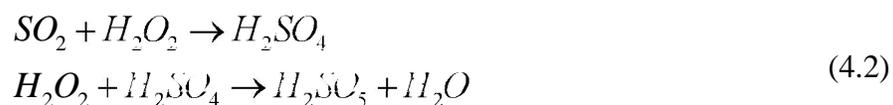
The Figure 4.10 also reveals that the hydrogen peroxide with 0.1M provides around 87% SO_2 removal efficiency than the sulphuric acid. When hydrogen peroxide is sprayed on the top of the column, it oxidizes SO_2 in the inlet gas and forms aqueous sulphuric acid as a by- product. Since hydrogen

peroxide is an effective and eco-friendly oxidizing agent, it enhances the oxidation process. A fast exothermic reaction takes place with SO_2 and produces sulphuric acid with no other secondary pollutant to the atmosphere. Though NaOH solution provides better removal efficiency, hydrogen peroxide is chosen as an absorbent for this study to produce a by-product and it does not produce the effluent into the atmosphere. Also, hydrogen peroxide is less toxic, safe for storage, non pollutant and easily decomposes into water and oxygen. The results obtained by the experiments provide a quite satisfactory agreement with the results provided by Colle et al (2004). There is not much variation absorbed for various SO_2 inlet concentrations for various absorbents.

4.3.2 Effect of H_2SO_4 + Externally Added H_2O_2 on SO_2 Removal Efficiency

Though pure hydrogen peroxide and mixed solution including $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$ produce better removal efficiency (85-90%), quite interesting results are obtained for H_2SO_4 with externally added H_2O_2 .

Sulphuric acid (H_2SO_4) is oxidized by hydrogen peroxide (H_2O_2) into di-peroxide ($\text{H}_2\text{S}_2\text{O}_8$) and the unstable mono-peroxy-sulphuric acid (H_2SO_5) called as caro's acid. It oxidizes SO_2 to H_2SO_4 a process that is used for cleaning gases. The stoichiometric amount needed of H_2O_2 for the oxidation is 1mol H_2O_2 per mol SO_2 . The reaction equation and the stoichiometric amount in weight units (kg) given as:



$$\frac{34 \frac{\text{kg}_{\text{H}_2\text{O}_2}}{\text{kmol}_{\text{H}_2\text{O}_2}}}{64.06 \frac{\text{kg}_{\text{SO}_2}}{\text{kmol}_{\text{H}_2\text{O}_2}}} \cdot 1 \frac{\text{kmol}_{\text{SO}_2}}{\text{kmol}_{\text{H}_2\text{O}_2}} = 0.53 \frac{\text{kg}_{\text{H}_2\text{O}_2}}{\text{kg}_{\text{SO}_2}} \quad (4.3)$$

The stoichiometric amount of H_2O_2 is sufficient for an effective oxidation. Adding more H_2O_2 has no effect on the oxidation process meanwhile less H_2O_2 leads to only partial oxidation. The amount of SO_2 that is not oxidized with the help of H_2O_2 to H_2SO_4 just dissolves.

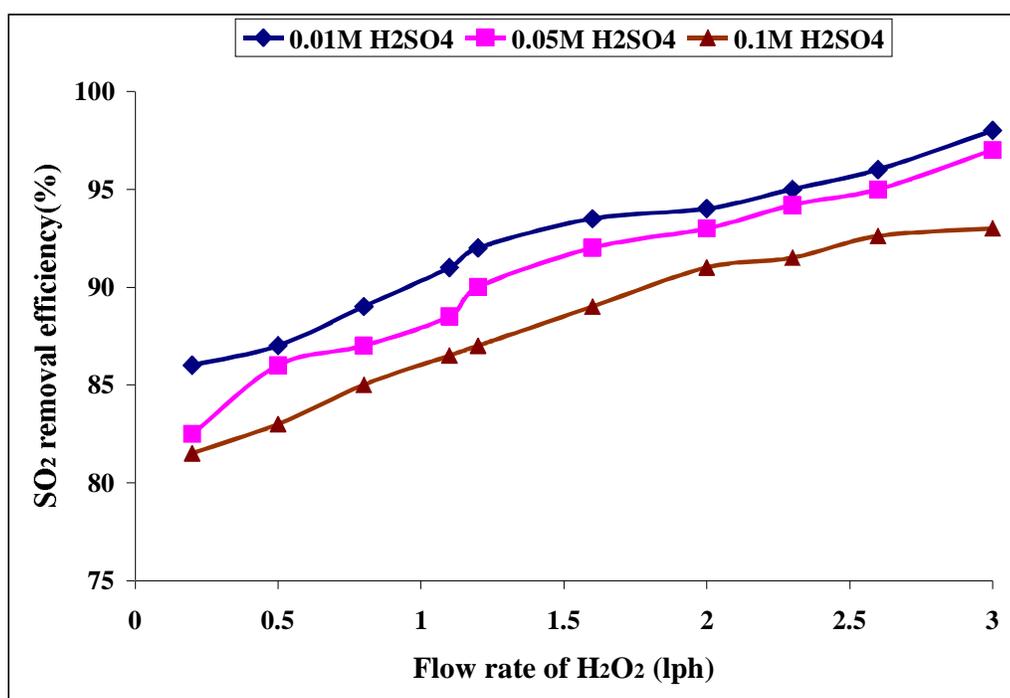


Figure 4.11 Effect of 0.1M $\text{H}_2\text{O}_2 + \text{H}_2\text{SO}_4$ various concentrations on SO_2 removal efficiency

For this oxidation reaction, 3 lph of H_2O_2 is added for the absorption process. Also, in the mixing tank, along with partially absorbed H_2O_2 , fresh H_2O_2 is externally added to replace the consumed H_2O_2 . Hence 0.1 M H_2O_2 is added externally with various concentrations of H_2SO_4 and its effect on SO_2 removal efficiency is recorded and shown in Figure 4.11.

From the Figure 4.11, it is observed that the flow rate of H_2O_2 has a direct influence on the SO_2 removal efficiency. From the Figure 4.11, it is clear that the increase in sulphuric acid concentrations reduces the SO_2 removal efficiency. In this work, the removal efficiency obtained for externally added H_2O_2 is 98.4%.

The SO_2 removal efficiency for different concentrations of H_2SO_4 is also analysed and illustrated in Figure 4.11. The partial pressure of SO_2 increases relative to the molality of sulphuric acid in the solution, i.e., the solubility of SO_2 decreases with the addition of H_2SO_4 . The degree of dissociation of SO_2 via reaction decreases as a result of the lower concentration of hydrogen ions.

Similar result is ensured from the results obtained by Colle et al (2004). In their studies, the mixed solution consists of H_2SO_4 (1.225 M) with H_2O_2 (0.2M) and H_2SO_4 (2.21 M) with H_2O_2 (0.2M) and SO_2 removal efficiency is reduced around 76% and 70% respectively. As compared to the results of Colle et al (2004), present study increases the SO_2 removal efficiency by 98.4% due to the addition of externally added H_2O_2 . Hence it is considered as an absorbent for further studies.

4.3.3 Effect of L_m/G_m Ratio on SO_2 Removal Efficiency

The experimentation is carried out to optimize the L_m/G_m ratio for the absorbent that contains H_2SO_4 with externally added H_2O_2 solutions. The experiments are conducted by varying liquid and gas flow rate with different L_m/G_m ratio for the following 4 cases as shown in Figure 4.12.

Case 1: 25 litre/hr / 7m³/hr

Case 2: 50 litre/hr / 13m³/hr

Case 3:75 litre/hr /21m³/hr

Case 4:150 litre/hr /40m³/hr

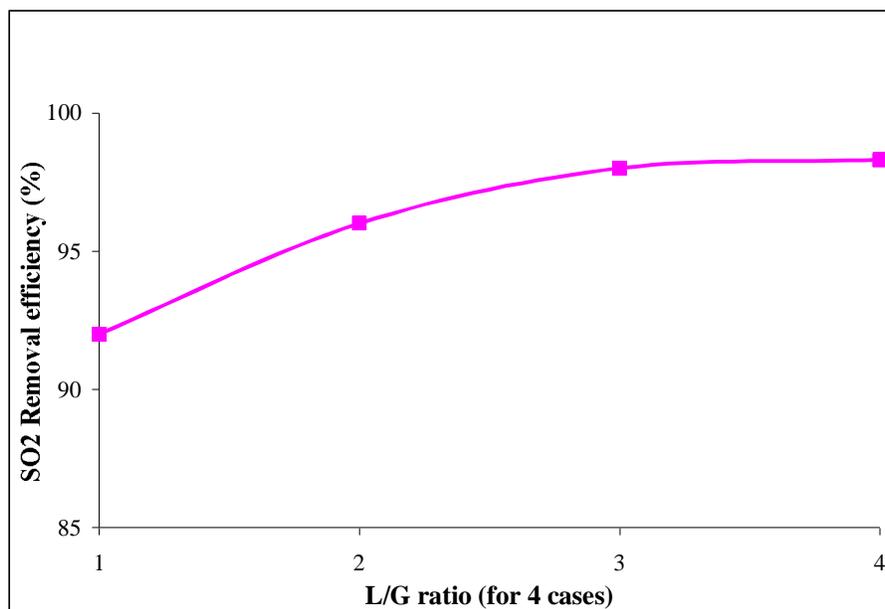


Figure 4.12 Effect of L_m/G_m ratio on SO₂ removal efficiency

The L_m/G_m ratios given above are calculated based on the physical modelling detailed in section 3.1.1. The Figure 4.12 reveals that the increase in L_m/G_m ratio increases the absorption rate. The absorption study is limited to an L_m/G_m ratio of 3.75 l/m³ since further increase in L_m/G_m ratio results in flooding over the column. Hence the L_m/G_m ratio is optimized at 3.75 l/m³ for further experimentation.

4.3.4 Effect of Packing Material and Packed Height on SO₂ Removal Efficiency

The selection of packing material plays a key role in determining the absorption rate in the packed column. Different types of packing material are used, among which ceramic rings and polypropylene pall rings are considered for this experimental study. Ceramic ring with 10 mm diameter,

polypropylene pall rings with 10 mm and 15 mm diameter are chosen for experimental studies. Among these, polypropylene pall ring with 15 mm produces more than 95% removal efficiency as shown in Figure 4.13. Though the ceramic ring is still used in industrial packed column, polypropylene pall ring provides increased liquid distribution characteristics since it is designed with opening stripes of the surfaces. Hence the polypropylene pall ring with 15 mm diameter is considered for further studies.

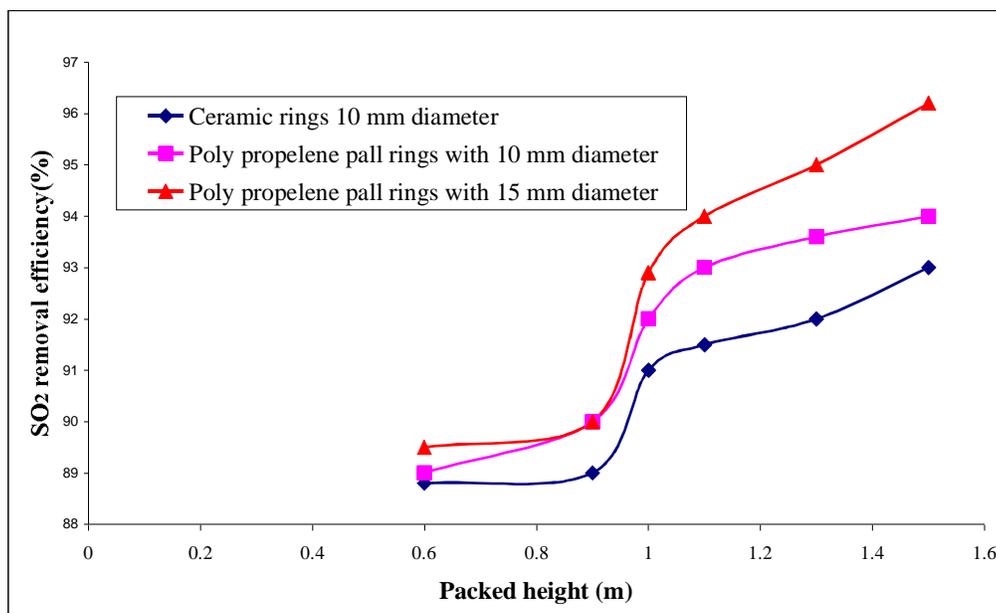


Figure 4.13 Effect of packing material and packed height on SO₂ removal efficiency

Figure 4.13 also indicates that the increase in packed height increases SO₂ removal efficiency since more packed area gives more gas-liquid interaction. For the present study, packed height is optimized as 1m since the packed height increases beyond 1m and more liquid is accumulated at the top of the packed column.

For flue gas desulphurization process, sulphuric acid with externally added hydrogen peroxide is an attractive alternative which brings down the solid and other secondary waste produced by other FGD techniques. 0.01M Sulphuric acid with externally added 0.1M hydrogen peroxide produces 98.5% SO₂ removal efficiency as compared to the other combinations. A better control action can be provided by regulating the flow rate of hydrogen peroxide, since it has a direct influence on SO₂ removal efficiency. This pilot plant packed column developed with 150 mm inner diameter can be used to receive a maximum of 150 litre/hr liquid flow rate and 40 m³/hr gas flow rate. Packed height is selected as 1m and polypropylene pall rings with 15 mm diameter are chosen for analysis because they produced better SO₂ removal efficiency. With these optimized parameters, a suitable controller will be developed to reduce the SO₂ emission, by regulating the flow rate of externally added H₂O₂.

4.4 MODEL DEVELOPMENT

From the lab scale experimental system, the experiment is conducted to find the influence of externally added hydrogen peroxide on the SO₂ removal efficiency.

For the model development, in the open loop scheme, a process reaction curve is recorded by regulating H₂O₂ for the DAQ output of 20% to 100% as shown in Figures 4.14-4.18. The curve describes the nature of liquid–gas interaction and level of complexity in terms of nonlinearity and time varying nature of the process.

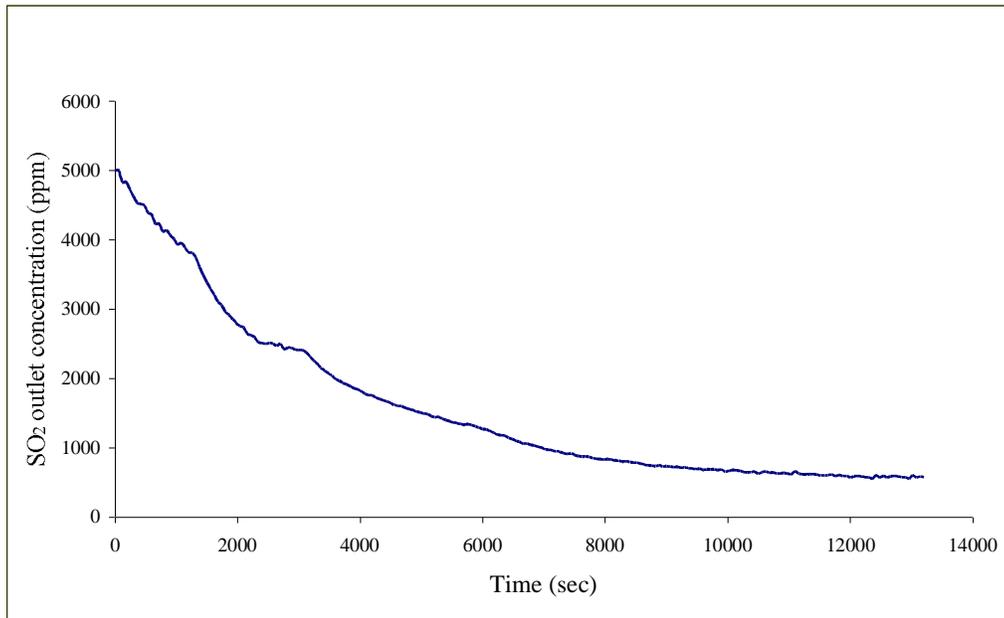


Figure 4.14 Process reaction curve for 20% DAQ opening

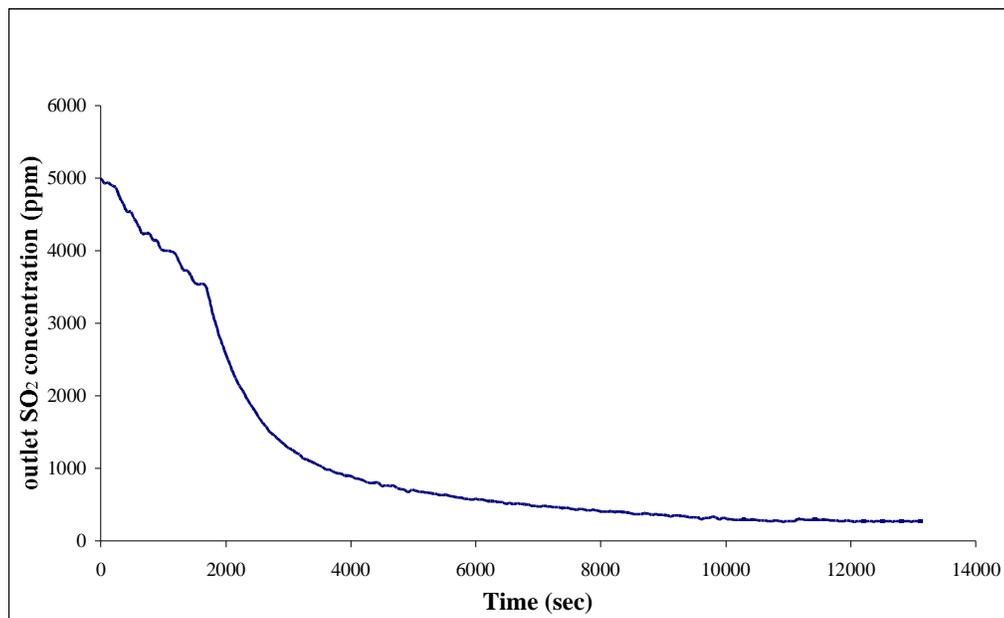


Figure 4.15 Process reaction curve for 40% DAQ opening

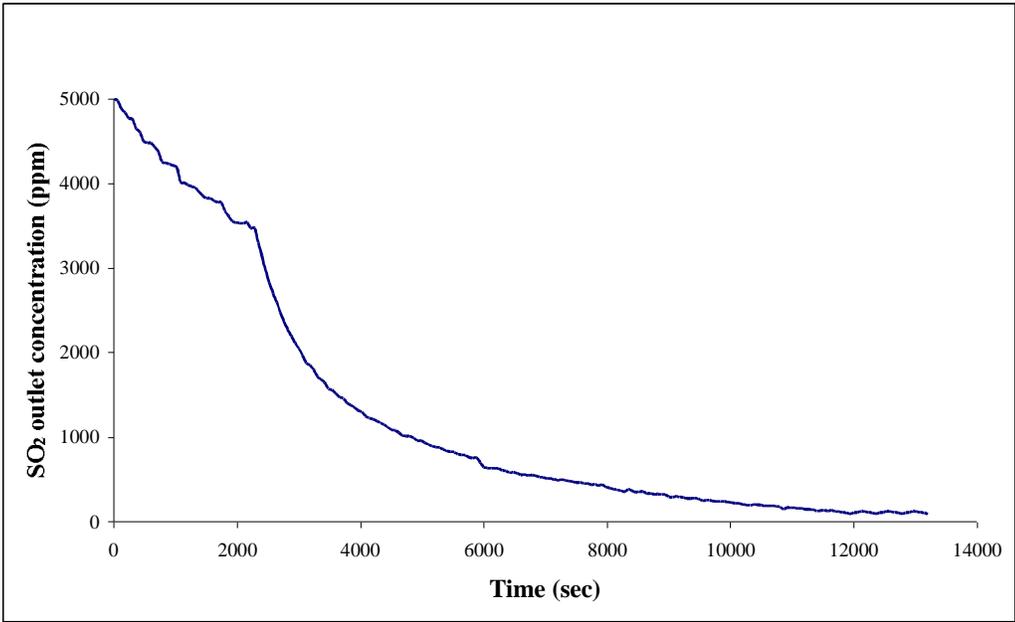


Figure 4.16 Process reaction curve for 60% DAQ opening

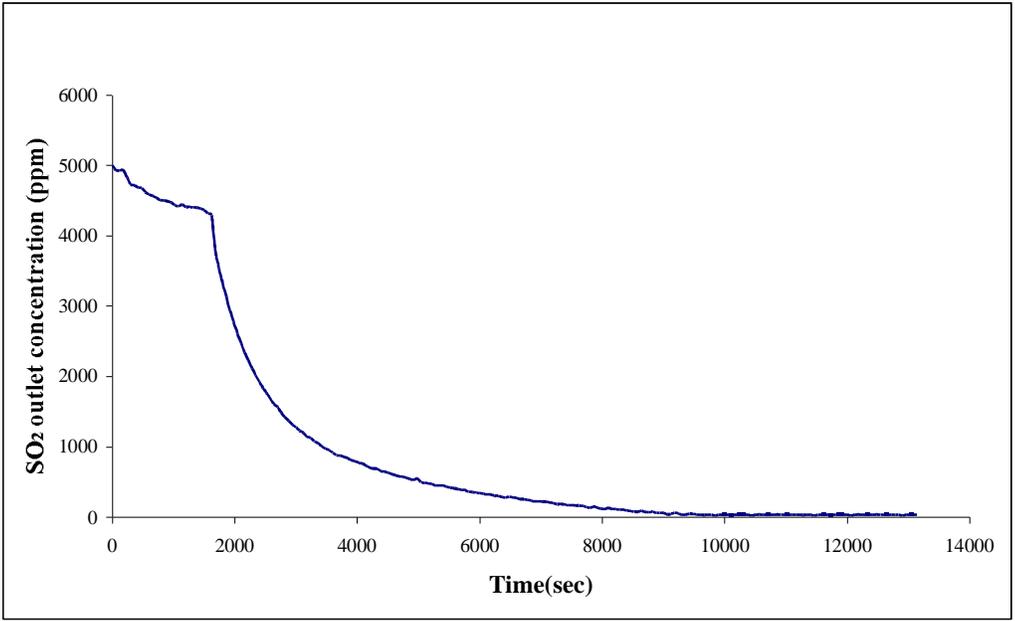


Figure 4.17 Process reaction curve for 80% DAQ opening

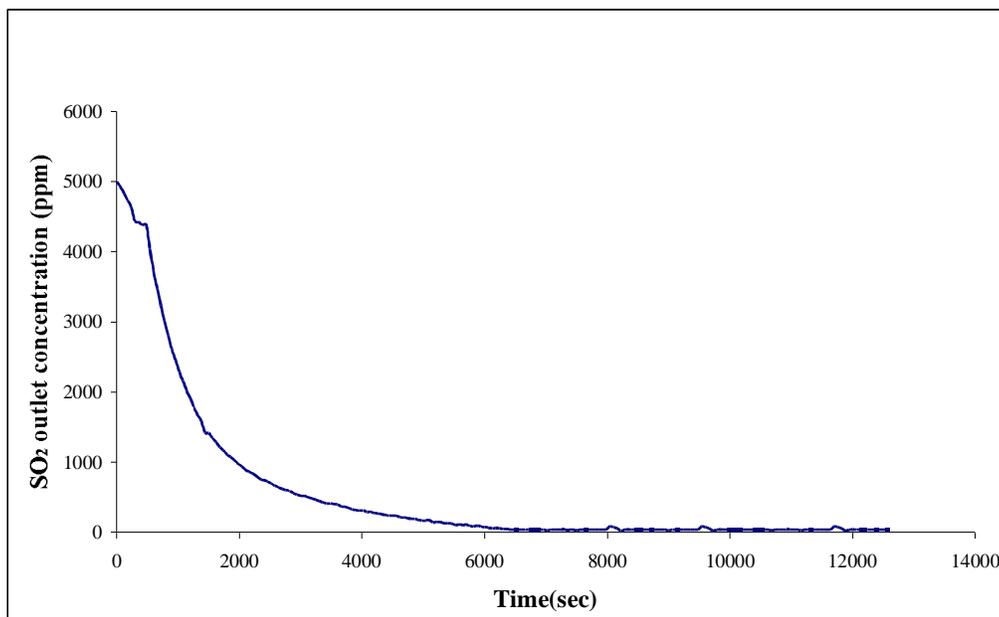


Figure 4.18 Process reaction curve for 100% DAQ opening

From the Figures 4.14-4.18, it is clear that the flow rate of hydrogen peroxide has a direct influence on the SO₂ removal efficiency. The SO₂ outlet concentration reaches towards a minimum value for the increase in flow rate of the H₂O₂ from 0-3 lph. As shown in figures 4.17 and 4.18, the SO₂ outlet concentration reaches almost the same minimum value for 80% and 100% DAQ opening. But for the 100% DAQ opening, SO₂ outlet concentration reaches minimum value at 6000 sec where as for 80% DAQ, SO₂ outlet concentration reaches minimum value at 9000 sec. This ensures the influence of flow rate of H₂O₂ on SO₂ emission control process.

They also reveal that the process is non-linear and stable in nature. Hence, the First Order Plus Time Delay (FOPTD) transfer function

($G_p(S) = \frac{K_p}{\tau_p S + 1} e^{-\theta S}$) model is considered to represent the SO₂ emission control

process. Based on the design procedure detailed in Gopal 2002, worst case or average case model can be chosen for model development. Based on the two

point method (Gobal 2002), the first order model parameters (process gain K_p , process time constant τ_p and time delay θ) are computed from the process reaction curves and they are furnished in Table 4.1.

Table 4.1 Identified model parameters at different operating points of outlet SO₂ concentrations

Operating point				K_p (%/%)	τ_p (Min)	θ (Min)
% DAQ opening	Flow rate of H ₂ O ₂ (lph)	Outlet SO ₂ Concentration (ppm)	SO ₂ removal efficiency (%)			
20	0.5	592	90.16	3.536	15.32	14.62
40	1	232	95.36	2.364	16.43	21.91
60	1.6	63	98.74	1.646	5.13	35.59
80	2.3	36	99.28	1.241	17.88	22.84
100	3	24	99.52	0.9952	14.88	13.58
Average				1.5616	13.58	23.48

From the Table 4.1, the average values of K_p , τ_p and θ are taken as the model parameters and they are represented as,

$$G_p(S) = \frac{K_p}{\tau_p S + 1} e^{-\theta S} = \frac{1.5616}{13.58S + 1} e^{-23.48S} \quad (4.2)$$

The identified transfer function model given in equation 4.2 is used as a transfer function for the SO₂ emission control process and it is used for controller studies.