

MAJOR SCIENTIFIC AND TECHNOLOGICAL ACHIEVEMENTS

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1. DESIGN OF MECHANICALLY AGITATED REACTORS

Mechanically agitated reactors are used for a variety of operations in the Chemical Process Industry. These equipment are most common and used in refineries, manufacture of petrochemicals, polymers, pharmaceuticals, dyes, organic and inorganic synthesis, hydrometallurgical operations and manufacture of specialty and performance chemicals. However, the design of these equipment has been still an art. This is basically because of the complex hydrodynamic behaviour of these equipment. Another difficulty has been the lack of understanding of the relationship between the hydrodynamics and the performance characteristics of the mechanically agitated reactors. Depending upon the specific duty for which this equipment is to be used, the rate controlling step may be one or many of the following: (i) suspension of solid particles (ii) wall heat transfer (iii) gas-liquid mass transfer (iv) solid-liquid mass transfer (v) the extent of mixing in all the phases and (vi) shear stress distribution. The flow pattern in the reactors needs to be adjusted in such a way as to enhance the rates of the above steps. However, the flow pattern which is ideal for one job may not be useful for another job. For instance, the flow patterns required for solid suspension and heat transfer are entirely different. By properly designing the impeller, the liquid flow (average velocity and intensity of turbulence) near the bottom can be generated in such a way that the power is efficiently used for the purpose of solid suspension.

Professor Joshi has measured the stability of large number of enzymes over a wide range of shear stress fields. He has addressed the problem of optimization of impeller design and power consumption which needs to satisfy the contrasting demands of efficient gas dispersion on one hand and viability of enzymes, proteins, plant cells and animal cells on the other hand.

Professor Joshi has made extensive measurements of mass transfer coefficient, blending, solid suspension, gas dispersion, liquid-liquid dispersion, etc. over a wide range of tank and impeller diameters, impeller design and physical properties of gas, liquid and solid phases. He has recommended procedures for the estimation of these design parameters.

Professor Joshi developed a systematic stepwise strategy for developing novel efficient designs. As a first step, detailed flow patterns have been measured using the most sophisticated available technique of laser-Doppler anemometer (LDA) and particle image velocimeter. Fifty different designs of axial, radial and tangential flow impellers have been examined. Measurements have been made for the three components of mean velocity, all the components of shear and turbulent stresses and turbulent kinetic energy. Professor Joshi has proposed a new method for the estimation of turbulent energy dissipation rate. Simulations of these impellers have been performed using computational fluid dynamics. He has employed all the forms of k - ϵ , RSM and LES models as well as models for impeller rotation and presented relative merits of these models. The predicted flow pattern has been related to design objectives such as blending, heat transfer, solid suspension, gas dispersion, liquid dispersion, etc. The predicted values of these design parameters have been compared with actual measurements over a wide range of tank diameters upto 1.5 m diameter and 50 impeller designs. Based on these comparisons rational recommendations have been made which are expected to be useful to practicing engineers, particularly, in terms of the selection of the optimum impeller design and the power consumption.

2. DESIGN OF SPARGED REACTORS

2.1. A systematic procedure has also been developed for the design of sparged reactors. As a first step, the laser anemometry has been employed for the accurate flow measurements in multiphase gas-liquid reactors. He has developed new procedures for (a) improving the signal to noise ratio (b) for the simultaneous estimation of bubble and liquid velocities from the LDA signals (c) measurement of bubble size distribution and the void fraction. Measurements have also been made close to the gas-liquid interface in the absence and presence of chemical reactions. Marangoni effect has also been measured. This is a very commendable and extremely useful contribution.

2.2. Professor Joshi has made significant contribution in the computational fluid dynamics for multiphase systems. During the past fifty years, there has been a continuous attempt to develop the governing equations for two phase flows. The development has been mainly on three fronts: (a) formulation of interfacial force (b) closure problem for eddy viscosity and (c) modelling of correlations arising out of Reynolds averaging procedure. A comprehensive analysis and critical review of the published literature has been carried out. The present status of our understanding of the drag force, virtual mass force and lift force has been brought out and the physical significance of different formulations has been presented. The

mechanism of energy transfer from gas phase to liquid phase has been explained.

2.3. The developments in closure problem have been most dramatic. The progress of the past twenty years has been critically analyzed and the chronology of development has been presented. The two-equation $k-\varepsilon$ model has been in wide use in the recent past. The various methods of discretization and solution procedure have been described and their relative merits presented. Discussions have been provided on several numerical issues such as grid size independence, role of initial guess values and damping parameters, the effect of internal iterations, rate of convergence, accuracy, etc. Sensitivity of $k-\varepsilon$ model parameters has been presented. The sensitivity of interface force terms (such as drag coefficient, virtual mass coefficient, radial lift coefficient, energy transfer factor and dispersion coefficient) has also been examined. The role of different turbulence models such as $k-\varepsilon$, Reynolds stress model and large eddy simulations has been extensively analyzed and the relative merits established.

An attempt has been made to develop a complete correspondence between an operation of a real column and the model simulation. The effects of superficial gas velocity, column diameter and bubble slip velocity on the flow pattern have been examined. A review of the experimental measurements of flow patterns has been presented. The numerical simulation and experimental observations of various macro structures have been analysed and the current status presented. Recommendations have been made for future research in this area.

2.4. Professor Joshi has pioneered, with a measure of success, the development of unified procedures for the estimation of gas, liquid and solid dispersion coefficients, pressure drop, wall heat transfer coefficients and mass transfer coefficients. For one design parameter, a single equation has been shown to hold for the most complex case of three phase sparged reactors as one extreme and the simple case of single phase pipe flow as the another extreme. As in-between cases, the design parameters for bubble columns, loop reactors, spray columns and solid-liquid fluidized beds can be estimated using the same procedure even though the variation in the value of design parameter is as high as 1000. Professor Joshi has been able to utilize the predictive procedures successfully in forecasting the performance of large size commercial columns.

2.5. Professor Joshi has been able to explain many apparent discrepancies and peculiar phenomena exhibited by multiphase systems: (a) Rational procedures have been developed for the estimation of critical superficial gas velocity for suspension of solid particles and for the prediction of intermixing/segregation in fluidized beds having binary particle sizes. (b) Explanation has been provided for the contraction/expansion of a solid-liquid fluidized bed when a gas is introduced. (c) The hindered settling velocity of particles and hindered rise velocity of bubbles and drops have been predicted with the favorable comparison with the published information. This leads to the satisfactory estimation of dispersed phase hold-up in the homogeneous regime. (d) The bubble rise velocity and particle settling velocities have been predicted in the heterogeneous regime. (e) On the basis of force and energy balance, it has been shown that the buoyancy force on a particle (or bubble or drop) depends upon fluid density and not the suspension density. (f) A systematic and coherent procedure has been developed for the design of external loop and internal loop air-lift reactors.

2.6. Professor Joshi has analysed the performance of all the types of gas distributors which include sieve plates, single and multiple rings, pipes, etc. In addition to the distributor design, the performance depends upon the design of upstream hardware (gas chamber, inlet nozzle, etc.) and the downstream pressure field. Experimental measurements and CFD simulations have been made regarding the uniformity of sparging, pressure drop and weeping. Recommendations have been made for the selection and optimum design of gas distributors.

2.7. Professor Joshi has evolved some novel designs of multiphase sparged reactors. These include sectionalized bubble columns, air-lift fluidized beds and horizontal sparged reactors. These novel designs are 3 to 4 times efficient in terms of axial mixing, Reynolds stresses and mass transfer coefficients, respectively. He has designed commercial size sectionalized bubble columns and horizontal sparged reactors which are giving satisfactory and desired performance on industrial scale. On this subject of multiphase reactor design, Professor Joshi has written ten monographs. These are very widely used in industry throughout the world. Further, professor Joshi has himself designed several commercial size reactors.

(a) Bubble columns have been designed for the process of catalytic hydrogenation. In the case of hydrogen peroxide manufacture, the design has been found to be superior to that supplied by an international vendor. The new design gives much higher productivity and selectivity.

(b) Bubble columns have been designed for the chlorination of toluene (side chain), toluene (ring) benzene, phenol. Bubble columns have also been designed for the isobutylation of cresol, hydroquinone

and anisole; ammonolysis of fatty acids, nicotinic acid; air oxidation of a variety of compounds. Hydrobromination of α -olefins and hydrochlorination of lauryl alcohol. Bubble columns are also needed in the manufacture of several pharmaceutical products. Both batch and continuous modes of operation have been designed and all these equipment are in successful commercial operation.

(c) Liquid-liquid spray columns have been designed for the manufacture of fatty acids. This is a very high temperature and high pressure operation. Liquid-liquid spray columns have also been designed for the duties of neutralization and direct contact heat transfer. All these equipment are in successful commercial operation.

(d) Liquid-gas spray columns have been designed for the pollution abatement of NO_x and Sox. Spray dryers have been developed and these are in successful commercial operation.

(e) Solid-liquid fluidized beds were designed for ion exchange operation for the purification of crude glycerine. Solid-liquid fluidized beds were also used for solvent crystallization and melt crystallization.

(f) Packed columns have been designed for the complex problem of NO_x absorption: both for the manufacture of nitric acid and for pollution abatement. Dry hydrochloric acid gas generator has been designed and standard models for different capacities have been established. A large number of packed columns have also been designed for the usual application of absorption and distillation. The smallest laboratory size column was 50 mm in diameter and containing 50 theoretical stages. Columns upto 5 m in diameter and 20 m height have been designed and all these equipment are being used continuously for commercial production.

3. ANALYSIS OF HYDRODYNAMIC STABILITY OF MULTIPHASE REACTORS

Professor Joshi has examined the hydrodynamic stability of all the multiphase reactors. In industry, gas-liquid bubble columns, solid-liquid fluidized beds, gas-liquid-solid fluidized beds and transport reactors are very popular multiphase reactors. These reactors operate in either of the two characteristic regimes: homogeneous or particulate and the heterogeneous (aggregative). The rates of heat, mass, momentum transfer and mixing are quite different in these two regimes. Therefore, it is important to know the range of operating and design parameters over which the two regimes prevail and the conditions under which the transition occurs. This subject has been extensively investigated during the past fifty years and numerous fundamental, semi-empirical and empirical approaches have been reported for the prediction of transition. All these studies have been analysed by Professor Joshi. Further, unified and generalized criteria have been developed. The new criterion has been successful for practically all the multiphase systems and over a wide range of design and operating conditions. In view of these, the past published results have been discussed. Stability maps have been presented. For several multi phase reactors, comprehensive comparison has been presented between the predicted and experimental conditions of transitions. The characteristic differences among the various multiphase systems have been brought out. Suggestions have been made for the future work.

4. PHYSICS OF TURBULENCE AND ANALYSIS OF TRANSPORT PHENOMENA

Chemical processing deals with the activities necessary for deciding the best possible hardware and operating protocols to carry out desired transformation of raw materials into value added products. The successful design requires expertise in thermodynamics, chemistry and catalysis, reaction engineering, fluid dynamics, mixing, heat and mass transfer. The first three disciplines explain transformation at the molecular level and hence the information collected at the laboratory scale applies equally to the industrial scale. However, the equipment scale dependent phenomena such as mass and heat transfer and mixing need to be understood for reliable and efficient design of equipment for unit operations and processes. Till date, design engineers rely on the accumulated knowledge (in the form of empirical and semi-empirical correlations) and the pilot plant experience with various reactor arrangements. There are almost 400 different types of reactors and multiphase contactors in practice which are designed by modifications in few conventional hardware configurations (straight and coiled pipes, jets and venturies, ejectors, packed columns (random and structured packings), falling and agitated film contactors, staged column contactors, bubble columns, fluidized beds, stirred tanks, etc.). Once such modifications are successful they are reproduced in exact replica for other production facilities of the same chemical by the process licensors for the production at other scales, other than the tested range. By following the aforesaid procedure, the design

may prove unreliable (and/or expensive) due to the lack of in-depth understanding of transport phenomena. Thus in practice, all these plants are always over-designed for a given production rate. Such empirical practices lead to high capital and operating costs, long start up times, and expensive ways of solving plant problems. Further, such apparent overdesigns have resulted into underdesigns in several commercial operations. In addition, the selectivity levels may be low and lead to by-products, which in turn add a burden on the environment. The overdesign also means energy intensive operation.

In all the equipment, to achieve the set objectives, energy is supplied either by kinetic energy of continuous or dispersed phase (pipe flow and jet loop reactor), or by rotating solid bodies (impellers in case of stirred tanks, cylinders in centrifugal contactors, disk in rotating disc contactors, etc.), or through the introduction of the dispersed and continuous phases (bubble columns, spray columns, plate columns, fluidized beds, etc.) or film flows (falling and agitated film reactors, packed columns, trickle beds, etc.). For the optimum design with minimum power consumption, understanding of genesis and dynamics of turbulent flow structures is essential. Professor Joshi is working throughout his research career on the understanding of transport phenomena, how input energy is getting distributed and dissipated and the possible hardware changes by which energy can be made to dissipate at the desired locations, then the energy input can be brought down by at least 5-10 times. He has carried out energy balance of pipeline reactor, mechanically agitated contactors, bubble columns, solid-liquid fluidized beds, centrifugal extractors etc in late 70s and early 80s. With the advent of experimental, computational and mathematical tools, he had studied the scalewise distribution of turbulent kinetic energy, dissipation rate and other turbulent quantities. This exercise reflected that, not all the scales of turbulence contribute equivalently to improved transport rates and mixing. Hence, he found it important, to understand the basic mechanism of interaction of different scales of motions with the rates of different transport processes.

He has recommended a methodology for such analysis into following parts (1) flow visualization using advanced experimental and computational techniques (2) development of mathematical tools for post-processing of the experimental data (3) computational fluid dynamics (4) with the help of steps (2) and (3), to get quantitative information on the turbulent structures and mean flows (5) to establish the relationship between the structure properties and the transport rates (6) using the procedure (1) to (5), to redesign the existing equipments and confirm their performance by implementation.

He has carried out extensive measurements at solid fluid interfaces in jet loop reactor (JLR), condensation jet reactors (CJR), bubble columns (BC) and stirred tank reactors (STR) using laser Doppler anemometer, hot film anemometer using very high data rates (approximately 100-2000 Hz and 20 kHz respectively). These experiments have contributed significantly to the understanding of surface renewal patterns which contribute to heat and mass transfer at the interface. To understand the gross flow structures, he has carried out PIV measurements of JLR, CJR, STR and expanded bed reactors. These measurements have also proved useful to validate the CFD simulations. He has carried out DNS studies of particle systems and LES simulations of channel flow (CF), JLR, STR and BC to study the effect of instantaneous flow structures on the mixing and heat and mass transfer rates. Using LES simulation of CF, he has accurately quantified the limiting behavior of turbulent viscosity close to wall. The experimental and simulation data has been analysed using advanced mathematical tools to extract maximum relevant information about the flow structures. These techniques namely point techniques (variable interval time averaging, quadrant analysis, pattern recognition technique, windowed gradient average technique etc.), Fourier transform, eddy isolation method, discrete and continuous wavelet transform, linear intermittency measure and proper orthogonal decomposition (POD) techniques. He has also developed hybrid POD-wavelet technique which avoids limitations of both the techniques and incorporates advantages of these techniques.

He has analysed the HFA data in JLR and CJR using eddy isolation model (EIM) and continuous wavelet transform (CWT) based methodologies to evaluate eddy age distribution at these interfaces where distinction in distribution has been observed at the SL and VL interfaces. He also observed that only age distribution can not give accurate estimation of heat transfer rates and consideration of size, shape and energy of flow structures is important. Further, local heat transfer coefficients (HTC) have been evaluated experimentally as well as based on the eddy age and area distributions in the form of proposed "modified capacitance model".

These POD and wavelet techniques have been applied to reveal the dominant flow structures, their dynamics and length scales in six widely used industrial equipments (STR, BC, Taylor--Couette flow (annular contactor), ultrasonic reactor (USR), JLR and CF). The variation in the length scale of structures within an equipment, with the change in its operating conditions (Reynolds number and power input) or

change in its geometric configuration (sparger and impeller designs), was brought out in this work. The planar data set for POD analysis was obtained from particle image velocimetry (PIV) and large eddy simulation (LES) studies. The dominant spatial topology was analyzed by using the velocity and vorticity POD modes. The modes have revealed the following flow structures: the ascending streaks and bursts in channel flow, the vortex tube and leading edge vortices in jets, the irregular small chaotic vortices in Taylor-Couette flow, the variation in plume oscillation and flow structures in the vortical region of bubble column resulting from changes in sparger design, the high intensity vortices near the source of ultrasound in the ultrasonic reactor and the effect of impeller designs on dominant flow structures and near blade vortices in the stirred tank. The length scales of structures were obtained by applying image processing on the spatial modes. The dynamics of these flow structures in each of the items of equipment is captured by reconstructing the flow field using appropriate spatial and temporal modes that contribute to these structures. In STR, the length scales obtained showed that the small-sized coherent vortices behind the blade of impellers are more in number, while large-scale structures are of the order of around one-third of vessel size. In all the three cases of DT, PBT, HF and, it was seen that the dominant flow pattern possesses around 90% of the total energy, and the vortices found around the shear region along the periphery of respective impeller discharge stream of three impellers carry about 3% of the total energy. The lowest energy contribution amongst known flow structures was by the vortices near the blade of the impeller. They contribute around 1% of the energy in the total flow. For all the three impeller designs, one can observe a similar mean and deviation in length scale distribution. But, the skewness and kurtosis of length scale distribution were seen to be highest for HF and lowest for DT.

He has used wavelet transform modulus maxima (WTMM) methodology to study the evolution of structures and their interaction in a reduced dimensionality by evaluating the fractal spectra. Classification studies have been carried out using principal component analysis (PCA) of the fractal spectra. The results obtained showed clear classes for the six types of equipments and delineate regimes to obtain benchmark patterns of flow hydrodynamics based on PCA co-ordinates. This methodology offered a generalized way for the optimal design and operation of different types of reactors.

An energy spectrum can give vital information regarding the small scale dissipative range responsible for most of the energy dissipation. The fundamental basis of these cascade models is that the energy transfer occurring in the inertial range may be conceptualized as a cascade process wherein each eddy of size l subdivides into n_l pieces of size l/n_l in such a way that the energy flux per unit mass is redistributed unequally among the n_l subeddies. The unequal split of the energy flux is modeled as the source of intermittency. The models assume that the conservation of energy flux holds in one dimension, as it does in three dimensions. Most of these intermittency theories have been developed upon the seminal work of Kolmogorov's theory of isotropic turbulence. To understand the energy spectrum and the mechanism of energy transfer between the different scales, the data obtained from post-processing of experimental and CFD will help to reconstruct energy spectrum, which would improve the understanding of local dissipation rate, the space-filling nature of turbulence, and the size and shape distribution of structures. The CWT technique seems to be better suited for extracting the eddy size distribution, as it is probably capturing appropriate physics that envisages an unequal energetic and length wise distribution of eddy break up (as postulated by the PL model), which could be more realistic scenario. The local turbulence parameters (eddy diffusivity, local energy dissipation rate and local turbulent kinetic energy) have been estimated using all the methods and their relative comparisons has been presented.

After understanding the spectrum generated by known reactor geometry, the geometry of reactor can be modified in order to 'Design of Turbulence' to maximize the transport rates. By design of turbulence, he refers to selecting the hardware and operating conditions in such a manner that the size, energy and age distribution of eddies within the reactor would result in enhanced transport phenomena (high heat and mass transfer, low mixing time at low power/volume). The information regarding the flow structure dynamics should be used to design the turbulence. If one is able to know the size and age distribution of eddies that satisfies one's objectives (such as enhanced heat and mass transfer, and/or efficient mixing at low P/V), then one can select the hardware and operating conditions that enables us to achieve this. For example, in pipe flow, a good understanding of flow structure dynamics near the wall has enabled the use of turbulence promoters. Same can be used for other equipment. The present flow structure analysis can be extended to study the flow structure dynamics and length scales within the equipment operated at the same power per unit volume.

5. MODELLING AND SIMULATION OF MULTICOMPONENT GAS ABSORPTION : NO_x GASES

5.1. Manufacture of Nitric Acid

Professor Joshi has analysed one of the most complex cases of multiphase reactions, namely the absorption of nitrogen oxides (NO_x) in water and in alkaline solutions. He has developed computer programs for the selection of column diameter, air/NO_x ratio, liquid submergence on a plate and plate spacing (in a good design both of these parameters should vary from bottom to top), number of plates, temperature and pressure of operation. He has also optimized the process parameters for the condenser to be used before the adsorption column. Computer codes also have been developed for the simulation and optimization of the entire nitric acid plant.

The optimization strategy addresses important processes which include oxidation of ammonia to nitric oxide, heat recovery from product stream of ammonia oxidation reactor and absorption accompanied by complex chemical reactions of multi-component nitrogen oxide gases into water. In design and optimization of nitric acid process, it is essential to understand the rate controlling step for ammonia oxidation process, strategy to be adopted for heat exchanger network design, rates of mass transfer and chemical reaction for nitrogen oxide absorption and the combined effects of several equilibria. The work addresses these issues taking through the complexities in the above mentioned processes. The parametric sensitivity of few parameters such as ammonia to air ratio, excess oxygen/air, selectivity, power recovery based on the performance efficiency of compressor and expander, inlet and outlet nitrogen oxide composition in condenser and absorption column have been a part of the investigation either explicitly or implicitly. Further, for the absorption column, the effects of geometrical parameters, excess air, extent of absorption, product acid concentration, temperature and pressure have been analyzed for the purpose of optimization of nitric acid plant. All parameters having major influence on annualized cost of product acid have been analyzed and presented. The computer codes developed by Professor Joshi are very widely used internationally for the design of commercial size columns. Also, he has himself used this computer program for the design of several absorbers for the manufacture of nitric acid with capacities in the range of 1 to 50 tons/day. All these plants are in successful commercial operation. He has also carried out trouble shooting in a plant manufacturing 1250 tons/day of nitric acid.

5.2. Manufacture of Alkali Nitrites

When NO_x gases are absorbed in an alkaline solution, both nitrite and nitrate are formed. Nitrates are commercially less attractive and it is desirable that the selectivity towards the manufacture of nitrite is as high as possible. Professor Joshi has analyzed this problem on the basis of fundamental principles. He has optimized the process parameters such as temperature and pressure of operation, air/NO_x ratio and the values of mass transfer coefficients. He has shown that the selection of the absorber hardware (type and size of packings in packed column and plate design and plate spacing in plate column) is very important for the favorable selectivity. He has developed a comprehensive computer program and optimum design strategy. He has established the selectivity in the range of 90-98% (depending upon the alkali). He has designed several absorption columns for the manufacture of sodium nitrite with capacities in the range of 1-80 tons/day with selectivities higher than 98%. All these plants are in successful commercial operation.

5.3. Unified Model for NO_x Absorption in Aqueous Alkaline and Dilute Acidic Solutions

The absorption of NO_x gases in water and alkalies [NaOH, NH₄OH, Ca(OH)₂] provides commercially important products nitric acid and salts (nitrates and nitrites), respectively. This complex phenomena of mass transfer with chemical reactions is described quantitatively in terms of $[H\sqrt{(kD)}]_l$ values for $J=N_2O_3$, N_2O_4 . However, the reported value of $H\sqrt{(kD)}$ for N_2O_3 absorption in strong alkaline solution was 50 times its value in water. For the intermediate case of NO_x absorption in weak alkali Ca(OH)₂, it was necessary to have a mathematical model which incorporated the HNO₂ decomposition, as well as neutralization by alkali. This led to a unified model for NO_x absorption, which can be used for predicting point rates of NO_x absorption as well as selectivity, for various gas compositions and liquid phase pH. Parametric sensitivity has been reported. A comparison of the model predictions with data from patent on Ca(NO₂)₂ manufacture has been made to test the model validity.

5.4. Pollution Abatement of NO_x Gases

Professor Joshi has made very valuable and substantial contribution in the area of pollution abatement due to NO_x gases. The most important parameter in the NO_x pollution abatement (by wet scrubbing) is the oxidation state of NO_x gases. Professor Joshi has suggested the use of ozone or nitric acid

for proper adjustment of the ratio of divalent to tetravalent nitrogen oxides followed by absorption in water or aqueous urea solution. Urea decomposes to innocuous N_2 and CO_2 . Professor Joshi has designed plants at five locations which are in successful commercial operation. This strategy is further developed and commercialized by an international vendor which **also earned the prestigious Kirkpatrick Award of Chemical Engineering** (the McGraw Hill Publication). He has also designed several plants using alkali scrubbing for the beneficial manufacture of nitrites. Thus the liability of NO_x pollution problem has been converted to handsome assets. Professor Joshi has developed artificial intelligence software for the selection of reactive absorption for the pollution abatement of NO_x gases. He has also developed generalized design procedures for commercial equipment.

6. DEVELOPMENT OF NOVEL REACTOR DESIGNS

6.1. Novel Designs of Mechanically Agitated Gas-Liquid and Gas-Liquid-Solid Reactors

Gas-liquid and gas-liquid-solid reactions are very common in Chemical Process Industry and contribute to more than 50 percent of all the commercial chemical reactions. These reactions are usually carried out in mechanically agitated reactors due to their flexibility and reliability. In many gas-liquid reactions, the per pass conversion of the gas phase is low due to the limited residence time and/or low rate of chemical reaction. Therefore, for improving the gas phase utilization, recycle of the unreacted gas is needed. Some industrial examples include catalytic hydrogenation, alkylation, ozonolysis, oxidation, ammonolysis, ammoxidation, reductive amination, addition halogenation, hydrohalogenation, waste water treatment, froth floatation, etc.

The gas phase recycle can be achieved either by an external compressor or an external pump. Such external loops need safety precautions particularly when the materials are toxic and/or hazardous. Therefore, it is desirable that the gas recycle is made possible completely internally. One such design is a gas inducing type of agitated reactor (GIMAR). It is essentially similar to the conventional mechanically agitated reactor with two differences. (i) a stator is provided in GIMAR. It consists of a standpipe and a hood which covers the impeller. The stator assembly is suspended from the top. Slots are provided to the standpipe in the gas space for the introduction of gas phase (ii) a special design of impeller is used. When the impeller rotates, low pressure is generated in the impeller region. If this pressure is less than the gas phase pressure, the self induction starts.

Such a gas inducing type of agitated reactor (GIMAR) is much superior to the conventional mechanically agitated reactors. However, the gas induction ability decreases as the impeller submergence increases. Therefore, at relatively high liquid submergence, the GIMAR is not effective and the application gets restricted upto a reactor size of 500 litres. Further, the gas inducing impeller cannot suspend solid particles which act as a catalyst. These features have been impediments in the commercialization of GIMAR.

From the foregoing discussion, it is clear that the gas inducing impeller has to meet contradicting demands of gas induction, gas dispersion and solid suspension. For these three totally different objectives, Professor Joshi has developed a novel and energy efficient impeller design. Commercial scale reactors have been designed in the size range of 500 litres to 20 m^3 for a variety of catalytic hydrogenations. All these reactors are in successful operation. The performance of these reactors has been at par as compared to those best available in the world. The investment cost, however, is 5 to 10 times lower than the international cost.

6.2. Reactor for Cracking of Castor Oil and Methyl Reccinoleate

Thermal cracking of castor oil/methyl reccinoleate gives undecylenic acid (or its methyl ester) and 2-ethyl hexanol. The cracking temperature is in the range of $300\text{-}450^\circ\text{C}$. The raw material and the products are heat sensitive and polymerize at high temperature. Therefore, for better values of yield, the reactor has to meet the contradicting demands of short residence time (of the order of fraction of a second) on one hand and heat transfer (heating upto reaction temperature) during the short residence time. Because of this problem, the best yield reported (even in the patented literature) is 73% of the theoretical. In practice, however, much lower yields are obtained.

Professor Joshi has developed a novel reactor design to meet these contradicting demands and he has achieved yields exceeding 95 %.

6.3. Novel Film Evaporators

Falling film and wiped film evaporators are very widely used for heat sensitive materials and high vacuum distillations. These are also used for very fast and/or instantaneous gas-liquid reactions. Commercially, reliable designs of falling film evaporators are not available due to film stability problems.

Some reliable models are prohibitively expensive. Further, the wiped or scraped film evaporators are reliable, however, they are very expensive. Because of this status, many commercial evaporations/distillations are still carried out by conventional methods using pool boiling. This practice has been resulting into substantial deterioration and residue formation. This is not only a material loss, but the residues pose pollution problems. There are plenty examples in India which fall under this category.

Professor Joshi has developed a new design evaporator which is reliable as well as less expensive. Another advantageous feature of the new equipment is that, the liquid phase residence time can be varied over a wide range. This is not possible in falling film and wiped film evaporators.

6.4. External Loop Air-Lift Reactors and Air-Lift Fluidized Beds

Professor Joshi has analyzed the flow pattern in the external loop air-lift reactors. He has recommended reliable design procedures for the selection of sparger location, area ratio of riser to downcomer and the reactor height. The final combination depends upon the process requirement and the rate controlling step such as gas-liquid mass transfer coefficient, heat transfer coefficient, mixing and the level of turbulent stresses in the liquid phase. The selectivity of some reactions get affected if the gas-liquid reactor is not properly designed. Professor Joshi has developed a reactor design for the chlorination of organic compound which has resulted into substantial improvement in the selectivity of the intermediate product.

Air-lift reactors are very widely used for aerobic fermentation. This case poses a very interesting design problem. The microorganisms/cells are stress sensitive. The viability, growth rate and product selectivity depend upon the stress level. Further, there is a maximum permissible level beyond which the turbulent stresses cannot be increased. However, the gas-liquid mass transfer coefficient increases with an increase in the level of turbulent stress. In addition, the motion of bubble itself can generate stresses beyond the permissible limit. Professor Joshi has developed a new design called air-lift fluidized bed. In this case, the regions of gas-liquid mass transfer and the biological reaction are isolated. In the individual regions, the parameters can be optimized separately. It is possible to arrive at such a design so that the overall mass transfer coefficient is even higher than bubble columns. In the reaction region, however, the stress levels can be reduced by a factor of 4 to 10 as compared with bubble columns. This reactor design is strongly recommended for aerobic biological treatment of aqueous waste streams. The new design needs less than ten times the residence time as compared with the popular designs such as surface aerators.

6.5. Sectionalized Bubble Columns

The extent of back mixing and the heat transfer rates are known to control the selectivity of several single phase and multiphase reactions. On the basis of fundamental understanding of hydrodynamics, Professor Joshi has recommended the design of a sectionalized bubble column. This design has been adopted in a commercial practice for the case of air oxidation. The improved design has resulted in an increase in the selectivity of desired product from 40 % to 65 %. Thus the new reactor has enabled to produce high value product by using the same raw materials and resulted into earnings amounting to millions of rupees.

6.6. Novel Design of Sono-Chemical Reactor

Ultrasound irradiation is known to enhance the rates of chemical reaction. Therefore, ultrasound catalysis has been the subject of active research during the past twenty years. However, this technique has not been exploited commercially because of two major problems: (i) difficulty in scaling-up ultrasound reactors. The uniform irradiation of relatively large mass has not been made possible because of very small effective range of ultrasound generators. (ii) very high cost for the generation of ultrasound.

Professor Joshi (together with his colleague) has developed a simple system of hydrodynamics cavitation in place of acoustic cavitation. He has shown that the hydrodynamic cavitation is 20 to 100 times less expensive as compared with acoustic cavitation. Further, the scale-up of hydrodynamics cavitation is straightforward. The new technique of hydrodynamics cavitation has been employed for a commercial process of fatty acid manufacture. The conventional hydrolysis process is carried out at high temperature (240-270 C) and pressure (40-70 atm) and needs large capital investment. Now it has been shown that these reactions can be carried out at ambient temperature and pressure using hydrodynamic cavitation.

6.7. Annular Centrifugal Extractor

The annular centrifugal extractors based on the Taylor-vortex flow have a great potential in chemical, nuclear, metallurgy and biotechnology industry. This equipment has been extensively studied during the past 80 years. However, most of the research has been focused on the flow instabilities. Relatively scanty information is available on the detailed quantitative flow pattern in single and multiphase flows, mixing and axial mixing, mass and heat transfer coefficients, drop and bubble size

distribution, and so on. Therefore, Professor Joshi has performed a systematic investigation using flow visualization techniques (LDA, PIV and HFA) and CFD simulations. Experiments have been performed for the phase capacities, fractional phase hold-ups, mass transfer coefficient, effective interfacial area, blending and axial mixing using 30, 75 and 250 mm rotors and have used power consumption range of 1 to 100 kW/ton. The 250 mm rotor ACE gives 5 to 7 tons/hr capacity which is a brilliant example of miniaturization. Professor Joshi has suggested a novel design by which plug flow is obtained on the annular side. The novel design gives five times capacity as compared with the best available commercial design (i.e. 25 to 30 tons/hr in place of 5 to 7 tons/hr).

6.8. Asymmetric Rotating Disc Contactors (ARDC)

These equipments are used for liquid-liquid extraction. The ARDC has a provision of phase separation as compared with the conventional rotating disc contactors (RDC). Professor Joshi has introduced novel design of the separator because of which substantial improvement occurs in stage efficiency. The new design also permits higher level of power consumption in the extraction zone, which in turn, permits substantial enhancement in the values of mass transfer coefficient and the effective interfacial area.

6.9. Moving Bed Reactors/Separators

Professor Joshi has introduced new features in the design of moving bed reactors. He has designed these equipments for the solid state polymerization (300 tons/day capacity) and several commercial applications of adsorptive and chromatographic separations.

7. AQUEOUS TWO PHASE EXTRACTION

For the purification of extracellular and intracellular fermentation products aqueous-aqueous two phase systems provide much superior environment as compared with aqueous-organic systems. Professor Joshi has measured the hydrodynamic and the mass transfer characteristics of spray, packed, plate and York-Scheibel columns using both polymer-polymer and polymer-salt two phase aqueous systems. He has recommended a stepwise design procedure for continuous counter current extraction columns depending upon fermentation system, the aqueous two phase system, the difficulty and the extent of separation. Professor Joshi has also investigated the mechanism of mass transfer of proteins (MW>3000) and has shown it to be different than the mass transfer of species having smaller sizes (MW<200).

8. MEMBRANE SEPARATIONS: PERVAPORATION

8.1. Separation of β and γ -picolines from water using elastomeric membranes has been studied. PDMS and EPDM membranes were found to afford separation with good selectivity and flux over the entire concentration range. Natural rubber and nitrile-butadiene rubber membranes caused only a shift in the binary distillation azeotropic composition. Data from sorption and permeation studies were used to calculate the heat of sorption and activation energy for diffusion as a function of the picoline concentration. The activation energy for diffusion was found to decrease with increasing picoline concentration in agreement with the theory of plasticization.

8.2. Pervaporative separation of aqueous solutions of propionic, butyric and iso-butyric acid has been studied using plain and filled silicone rubber membranes. All the three acids can be conveniently separated using plain silicone rubber membranes.

8.3. Sorption and permeation of aqueous alcohol (C_1 - C_4) through PVA membrane cross-linked with a multifunctional cross-linker is reported. The effect of temperature, feed concentration, cross-linker loading and the shape and size of the permeating species on pervaporation characteristics is investigated. Sorption isotherms of cross-linked PVA are obtained for the aqueous alcohol systems namely water + methanol, + ethanol, + n-propanol, + isopropanol, + n-butanol and + isobutanol. Values of activation energy for permeation (ΔE_p), diffusion (ΔE_d) and heat of sorption (ΔH_s) for water through cross-linked PVA are estimated. The value of ΔE_d for water was found to vary for all the water-alcohol systems (20-50 kJ mole⁻¹) covered in this work.

8.4. Pervaporative separation of benzene from its mixture with cyclohexane over the entire concentration range 0-100% benzene was studied using three copolymer membranes of acrylonitrile. The other monomers in the copolymers were selected on the basis of their solubility parameter values relative to those of benzene and cyclohexane. These were styrene, methyl methacrylate, and vinyl acetate. For each copolymer of acrylonitrile three different membranes with different copolymer compositions were

prepared. Copolymers of acrylonitrile with methyl methacrylate and vinyl acetate showed good selectivity and moderate flux ($0.075 \text{ kg}/(\text{m}^2 \text{ h})$) and 60-70 with a membrane of $10 \mu\text{m}$ thickness for a feed mixture containing 5% benzene). A copolymer of acrylonitrile with styrene showed comparatively higher flux but lower selectivity. The selectivities obtained with these copolymers are better than those reported in the literature.

8.5. Pervaporative dehydration of acetic acid over the entire concentration range of 0-100% is studied using four copolymer membranes of acrylonitrile and high performance Nafion and polyimide membranes. From each copolymer of acrylonitrile, three different membranes were produced with three different copolymer compositions. Polyimide showed high water selectivity but very low flux, while Nafion showed highest flux but lowest selectivity. Copolymers of acrylonitriles showed reasonable flux and selectivity behavior. Among the acrylonitrile copolymers, copolymers with hydroxyethyl methacrylate yielded water selectivity comparable to that of polyimide with much higher flux.

8.6. Pervaporative dehydration of ethylene glycol-water mixture was carried using PAA-PVA and PAAM-PVA interpenetrating polymer network (IPN) membranes. PAA-PVA IPN and PAAM-PVA IPN membranes were prepared by sequential IPN technique. The effects of concentration of water in the feed, and feed temperature on the sorption and permeation of water were studied. The effects of content of PAA in PAA-PVA IPN membrane on the permeation of water and mechanical strength of the membrane were also studied. The data obtained from sorption and permeation experiments were used to estimate the energy of activation for permeation (ΔE_p), energy of activation for diffusion (ΔE_d) and heat of sorption (ΔH_s) of water in the membrane. A model has been proposed to estimate the diffusion coefficient of water and ethylene glycol. It was found that PAA-PVA IPN membrane shows selective water transport compared to that of a PAAM-PVA IPN membrane.

8.7. Several copolymers of acrylonitrile were synthesized. Methanol selective membranes were prepared from these copolymers of acrylonitrile. The other monomers in the copolymers were selected on the basis of their solubility parameter values relative to those of methanol. These were hydroxy ethyl methacrylate, methacrylic acid and vinyl pyrrolidone. Thus, pervaporative separation of methanol from its mixture with ethylene glycol over the entire concentration range 0-100% methanol was studied using these copolymer membranes of acrylonitrile. For each copolymer of acrylonitrile three different membranes with different copolymer compositions were prepared. Copolymers of acrylonitrile with hydroxy ethyl methacrylate and methacrylic acid showed good selectivity and moderate flux for methanol (14.74 , 11.3 and $0.108 \text{ kg}/\text{m}^2 \text{ h}$, $0.0813 \text{ kg}/\text{m}^2 \text{ h}$, respectively, with membrane of $50 \mu\text{m}$ thickness for feed mixture containing 50% methanol). Copolymer of acrylonitrile with vinyl pyrrolidone showed comparable flux but methanol selectivity of this membrane was poor.

9. TECHNICAL SUPPORT TO LARGE SCALE AND MEDIUM SCALE INDUSTRIES

Professor Joshi has himself applied his research findings in the industrial design. He has been very active consultant to industry for the last 35 years. He is the most sought after academic consultant in India. He has designed a large number of equipment which are in successful commercial operation. Further, on the basis of fundamental principles, he has been able to increase the throughput and selectivity of a variety of chemicals in existing plants. This exercise has resulted into earnings/savings amounting to billions of rupees. Some of these cases are described below:

(1) INDIAN ORGANIC CHEMICALS, KHOPOLI: This assignment was related to the design of equipment for the manufacture of acetic anhydride, glyoxal, benzyl alcohol and benzaldehyde, design of system for the recovery of acetic acid from liquid effluent and pollution abatement for NO_x gases. The reactor designs were successfully evolved from the experience of research work. The capacities of acetic acid, acetic anhydride and benzaldehyde plants were increased by 40 to 50 % (amounting to earnings of 50 million rupees per year) by redesigning some of the existing equipment. The commercial process for the manufacture of acetic acid/acetic anhydride has been modified so as to increase the overall yield (savings range from 30 to 40 million rupees per year) and reduce the pollution load by 60 percent. This effort has not only reduced the pollution load but resulted into savings of more than four million rupees per year.

(2) LARSEN AND TOUBRO LTD., MUMBAI: This assignment was related to the design of ammonia absorption systems for a fertilizer plant. The fixed cost of the installed equipment was more than 20 million rupees.

(3) BOMBAY OIL INDUSTRIES PVT. LTD., MUMBAI: The assignment is concerned with (1) process development and design of equipment for castor oil products, oleoresins and hydrogenation of organic

compounds. A novel reactor was designed for the cracking of castor oil. The yields obtained were substantially higher than the best known in the world. (2) hydrobromination of styrene, olefins and undecylinic acid, etc., (3) design of continuous crystallization unit to separate saturated and unsaturated fatty acids, (4) treatment of aqueous waste-streams, (5) design of continuous splitting unit for the manufacture of fatty acids, (6) manufacture of fatty amides and nitriles using ammonolysis, (7) para and ortho tertiary butyl cyclohexanols (10,000 tons/year), (8) benzyl salicylate and (9) Hidion and a large number of perfumery compounds. All these processes are in operation. The capacities of many existing processes were increased by 50 to 100 %. The resulting increase in the turnover has been more than 2000 million rupees.

(4) ALKYL AMINES AND CHEMICALS LTD., MUMBAI: This assignment was related to the design of equipment (catalytic reactors, distillation columns, etc.) for increasing the capacity of a plant from 2000 TPA to 3600 TPA ethyl amines. A new plant has been designed for 20,000 TPA amines which is in successful operation. New plants have also been designed for the manufacture of dimethylamino propylamine by catalytic hydrogenation, furfural amine and large number of intermediates.

(5) HICO PRODCUTS LTD., MUMBAI: This assignment was related to the process development and design of equipment for the manufacture of lauryl chloride, glycol ethers and chlorosilanes. An improvement in the impeller designs substantially improved the selectivity in the ethylene oxide condensation reactions. The plant for glycol ethers was designed for the first time in India.

(6) STANDARD MILLS (Chemicals Div.) MUMBAI: The assignment was concerned with the assessment and improvement of performance of electrolytic cells in chloralkali plant.

(7) U.S. VITAMINS AND PHARMACEUTICAL CORPN. (INDIA) LTD., MUMBAI: This assignment was related to the design of some new equipment and the improvement in the performance of the existing units for vanillin plant. The selectivity of desired product was improved by 50 percent by improving the reactor design.

(8) CHEMO-PHARMA LABORATORIES, KALYAN: The assignment was related to the design of absorption system for NO_x gases for the manufacture of nitric acid at a capacity of 5 tons/day. The unit has been in continuous operation.

(9) QUALITY PRODUCTS, DOMBIVALI: This assignment was related to the development of process and design of equipment for the manufacture of butylated hydroxyl toluene and p-tert-butyl phenol. Professor Joshi has successfully designed a multiphase reactor and separation equipment which are in operation. The production rate is 15-20 tons/month. A plant has been designed for the manufacture of p-hydroxy anisole, butylated hydroxyl anisole and butylated hydroquinones. All these products are import substitutes.

(10) SAHYADRI DYESTUFFS LTD., PUNE: This assignment was related to the design of equipment for the manufacture of resorcinol, metanilic acid and sodium nitrite. In these cases also, the selectivity towards the desired product was increased. The plants are in operation at the increased level of selectivity.

(11) MODISON METAL LTD., MUMBAI: This assignment was related to the design of equipment for pollution abatement. Professor Joshi has designed a novel system for the NO_x removal which is in continuous operation. The design of reactor for the manufacture of oxalic acid was improved so as to give 25 percent increased yield. A new continuous plant has been designed for the manufacture of 3 tonnes/day of oxalic acid. The plant is in successful operation. The NO_x absorption efficiency is more than 98 %.

(12) RELIANCE HEAT TRANSFER, MUMBAI: A new design of a film evaporator has been evolved. This is much less expensive than the conventional wiped film evaporators and much more reliable than the falling film evaporators. The new design has resulted into substantial savings. It has made impact on material saving and substantial reduction on the pollution load.

(13) AARATI INDUSTRIES LTD., MUMBAI: This assignment is concerned with development and design of equipment for o-phenylene diamine, m-phenylene diamine, o-anisidine and p-anisidine by catalytic hydrogenation.

(14) UNITED PHOSPHORUS, LTD., MUMBAI: This assignment is related to the development of a process and design of equipment for the manufacture of an intermediate for a specialty pesticide by catalytic hydrogenation. The capacity and yields of existing plants have been improved for the manufacture of DVA chloride, meta phenoxy benzaldehyde, trimethoxy phosphite, triphenyl phosphite, etc. A large number of batch processes have been converted into continuous plants. New continuous plants have been designed for the manufacture of acephate (10,000 TPA), mancozeb (40,000 TPA) and glyphosate (40,000 TPA). The cost of production is globally competitive and permits the Indian industry to participate in the global market in a big way.

(15) RELIANCE INDUSTRIES LTD., MUMBAI: This assignment is related to the process intensification of manufacturing plant for tere-phthalic acid. This has resulted into enhancement in capacity, quality and selectivity. The new reactor design is commercially used by an international vendor for all the new plants since 1999. The capacity has increased by 80 percent and acetic acid consumption reduced by 50 percent. The assignment also included the development, design and implementation of new technology on solid state polymerization.

10. DEVELOPMENT OF PROCESSES FOR POLLUTION CONTROL

10.1. Treatment of Alcohol Distillery Waste

Ethyl alcohol is an important raw material for the manufacture of a variety of chemicals. For the manufacture of ethyl alcohol, a widely used method is fermentation followed by distillation. There are more than 300 distilleries throughout the world. Waste streams from these distilleries are most obnoxious. These are highly concentrated and the estimated load on environment is 5 billion kilograms of COD per year.

A novel and simple technique has been developed by professor Joshi. The process consists of heating the effluent stream to a temperature in the range of 170-230⁰C depending upon the nature of waste. More than 70 % of the COD gets separated from the effluent in the form of charred residue. The residue has properties similar to coal and has calorific value of 5000-6000 kcal/kg. The residue provides sufficient energy necessary for the treatment (heating upto 170-230⁰C) and the entire energy requirement of a distillery. For the treatment of remaining 30% COD, four methods have been developed (i) heat treatment similar to that used for 70% removal (ii) wet air oxidation (iii) anaerobic treatment and (iv) aerobic biological treatment. In all these cases, the parameters of each treatment have been optimized for the maximum cost effectiveness. The selection of one of the above technique is made depending upon the individual nature of the effluent.

Based on this technology, a commercial plant has been designed and it is in continuous operation.

Recently, Professor Joshi has developed even simple technique. It involves (i) optimization of process parameters in the distillery for reducing the volume and increasing the concentration of the effluent. This increases the energy efficiency of the process substantially (ii) direct contact evaporation is employed for concentration. This eliminates the problems of corrosion avoids the use of exodic material of construction (iii) incineration. The improved process is more than two times energy efficient as compared with anaerobic biological treatment and needs less than three times the capital investment. The most remarkable feature is that the effluent problem gets completely solved as against the partial solution offered by anaerobic biological treatment. The new technology is under implementation.

10.2. Detoxification of Cyanide Effluents

Professor Joshi has also developed new and simple technologies for the treatment of toxic and hazardous wastes such as inorganic cyanides and organic nitriles. The process consists of heating the effluent in the temperature range of 150-250⁰C depending upon the nature of compound. In some cases, the introduction of air may be necessary. In all the cases, the destruction of -CN group has been established close to 100%. Based on this strategy, two commercial size plants have been designed. These plants are in operation.

10.3. Regeneration of Spent Activated Carbon and Spent Activated Earth

Activated carbon and activated earths are very widely used in adsorption processes. We import large quantities of these materials and spend about 100 crores of valuable foreign exchange.

Professor Joshi has developed a simple technology for the regeneration of spent active earth and spent activated carbon. In most of the cases, close to 100% regeneration has been established. In the case of spent earth, which is used in the edible oil industry, the treatment not only regenerates the active earth but also recovers the valuable entrapped edible oil. Therefore, the earth regeneration is a very profitable process.

11. ENHANCEMENTS IN THROUGHPUT AND SELECTIVITY: ENERGY CONSERVATION AND REDUCTION OF POLLUTION LOAD

This is the area in which Professor Joshi has made a major impact in terms of financial gains. This activity consists of the following steps: (i) analysis of all the equipment in the existing plant and the determination of rate controlling step in each equipment (ii) to determine the key parameter which governs the rate controlling step (iii) to determine the rate controlling equipment in the plant (iv) to make some

modifications in the equipment with a view of enhancing the rate of rate controlling step.

Professor Joshi has analyzed several commercial plants and enhanced the capacity of the existing plants by 50 to 100%. In many cases, he has made a major impact in improving the selectivity of the desired product. There have been substantial savings in energy. This activity has resulted into gains amounting to crores of rupees. Further, the process modifications have concomitantly resulted in reduction in quantities of waste streams and hence load on environment. Following are some examples:

- (i) Manufacture of fatty acids by high temperature/high pressure hydrolysis.
- (ii) Manufacture of fatty acids by acidulation of castor oil.
- (iii) Distillation of fatty acid in plate columns and wiped film evaporators.
- (iv) Hydrogenation of fatty oil and fatty acids.
- (v) Manufacture of fatty nitriles, amides, tertiary amines and quaternary compounds.
- (vi) Manufacture of liquid fatty acids by solvent crystallization.
- (vii) Manufacture of methyl, ethyl, n-propyl, isopropyl and cyclohexyl amines.
- (viii) Manufacture of ampicillin and amoxycillin.
- (ix) Manufacture of oleoresins of pepper, turmeric and ginger.
- (x) Manufacture of paracetamol, analgin, phenyl glycine, isobutyl benzene, metanidazole and trinidadazole.
- (xi) Manufacture of nicotinic acid and nicotinamide.
- (xii) Manufacture of nitric acid and sodium nitrite.
- (xiii) Manufacture of resorcinol and metanalic acid.
- (xiv) Manufacture of vanillin.
- (xv) Manufacture of oxalic acid.
- (xvi) Manufacture of benzaldehyde and benzyl alcohol.
- (xvii) Manufacture of acetic acid and acetic anhydride.
- (xviii) Manufacture of glyoxal.
- (xix) Manufacture of a variety of esters such as ethyl acetate, benzyl acetate, benzyl benzoate, phthalic esters, benzyl salicylate, etc.
- (xx) Manufacture of p-chlorobenzoic acid, o-chlorobenzoic acid, 2,4 dichlorobenzoic acid, p-nitro benzoic acid, etc.
- (xxi) Manufacture of phenyl ethyl alcohol, p-t-butyl cyclohexanol and p-t-butyl cyclohexyl acetate.
- (xxii) Manufacture of glycol esters and ethers.
- (xxiii) Manufacture of monochloro acetic acid and EDTA.
- (xxiv) Manufacture of lauryl chloride.
- (xxv) Manufacture of ethoxylates of nonyl phenol, fatty amines, etc.
- (xxvi) Manufacture of butylated hydroxyl toluene and anisole, butylated hydroquinone, etc.
- (xxvii) Manufacture of p-phenylene diamine.
- (xxviii) Manufacture of terephthalic acid (PTA). Improvements have been made in a plant supplied by a world renowned organization.
- (xxix) Manufacture of DVA chloride.
- (xxx) Manufacture of meta phenoxy benzaldehyde.
- (xxxi) Manufacture of trimethoxy and triphenyl phosphite.
- (xxxii) Manufacture of phosphorus oxychloride.
- (xxxiii) Manufacture of acetate.
- (xxxiv) Manufacture of glyphosate.
- (xxxv) Manufacture of mancozeb.

12. TECHNICAL SUPPORT TO SMALL-SCALE INDUSTRY

Small scale industry plays an important role in India. While running small scale industry, several functions and aspects of the business are involved. The industry cannot usually afford full fledged consultants for each and every aspect. Therefore, it is desirable, as a social cause, that an attempt be made to extend the possible support. Professor Joshi has contributed substantially in this very important activity. He has provided his advice to more than twenty-five small scale industries for solving their technical problems.

For the development of four small scale industries, he has provided complete technical support: consisting of laboratory scale development, pilot plant studies, scale-up, design of full scale plant and

trouble shooting during the commercial operation. These industries are:

(i) Chemcrux Chemicals, Ankleshwar, Gujarat: Manufacture of O-chlorobenzoic acid, p-chlorobenzoic acid, 2,4-dichlorobenzoic acid, etc. A system for the recovery of NO_x gases has also been designed. The plant is in operation producing 50 tonnes/month of substituted benzoic acids. The company is now exporting their products.

(ii) Orgchem Industries, Dombivali, Maharashtra: Manufacture of p-phenylene diamine. The plant has been designed for the capacity of 300 tonnes/year and most of the production is export.

(iii) Maharashtra Aldehydes and Chemicals, Malad, Maharashtra: A continuous plant (consisting of 5 stirred tank reactors in series) has been designed for the first time. A recovery system for NO_x gases in the form of nitric acid was also designed.

(iv) N.S.Chemicals, Thane, Maharashtra: Manufacture of benzyl chloride. A batch and continuous plants were designed.

(v) Quality Industries Ltd., Dombivali: Manufacture of a spectrum of anti-oxidants such as butylated hydroxyl toluene, butylated hydroquinone, etc. This industry was started in mid seventies and the products were import substitutes. It saved foreign exchange.

In all the above cases, an attempt has been made to use all the raw materials completely and advantageously so that the pollution load is minimized. Treatment systems have also been designed for effluents.

13. SERVICE TO COMMUNITY AND SOCIETY

13.1. Design of Cooking Devices

In India, 40 percent of the energy is used in cooking where the energy efficiency is in the range of 5 to 20%. A new cooker has been designed with 40-60% energy efficiency. Several sizes for the utility of 4, 10, 50, 200, and 700 meals have been developed and fabricated. The cookers for mass cooking (200 and 700 persons) are now being used at large number of hostels, balwadis, Anandavan, community cooking, etc. The new designs are also being used for "noon meals" for school children.

13.2. Solar Energy

The usefulness of solar energy is well-known. However, this source has not been harnessed mainly because of the high capacity cost. With the present available technology, the capital cost is Rs. 40 crores/MW. However, these costs are 6, 4.5, 3 crores/MW for atomic, thermal and hydraulic energies, respectively. In order that the Solar energy be economical, the efficiency of energy collection needs to be improved. In addition, efficient and cost effective systems need to be developed for energy storage. Further, new materials need to be designed. All these efforts have been undertaken in the laboratory of Professor Joshi and the cost has been brought down to 12 crores/MW. Efforts are being made to reduce the cost further to less than Rs. 6 crores/MW. Then the solar energy will become attractive because of very low operating costs as compared with thermal, nuclear and hydraulic energies. The generation of solar power still is in need of technology improvement, the solar dryers and the solar air conditioning plants have been developed. The former is commercially successful while the latter is under field trial.

13.3. Community Education for Science Awareness

In India, 7% of the eligible students undergo higher education. However, those go for the science and technology stream are even less than 0.5%. It is known that a science based society has much better harmony. In view of this, Professor Joshi together with the Ph. D. students conducts about 250 workshops per year in the rural India. The participants are students from Schools and Junior Colleges. These workshops have become very popular and the attendance is in the range of 100 to 1400 per workshops. They are exposed to the scientific reasoning to the commonly made observations in day today life. The young students are encouraged to ask curious questions.

13.4 . Popularization of Research as a Profession

In the present day "knowledge Society" the wealth generated in any country (for instance, per capita income) is proportional to the knowledge generated in that country. Further, there is a fairly good correlation between per capita income and the number of Ph. Ds graduated per year in the area of Engineering and Technology (it appears that the number of Ph. Ds fairly well represents the knowledge generation). On the basis of this premise, the education policies of Japan and USA were developed even before seventies.

Professor Joshi visits undergraduate engineering colleges and explains the young minds about “Research as a Profession”. It not only adds multiple values to the society, it gives an opportunity of job satisfaction to the highest extent. The professional longevity (and hence health and mind) of science scientists and artists is known to be the highest. The efforts of Professor Joshi have resulted into substantial enhancement in the enrollment of students for Ph. D. programmes in Engineering and Technology. In his institution the enrollment has become twice in spite of increasingly lucrative jobs in industry.