MAGIC (Modular, Agile, Intensified and Continuous) Processes and Plants for Specialty Chemicals

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Abstract

In recent years, process intensification based on micro-devices has been in vogue. Despite significant research and several efforts in commercializing these, the adoption of micro-devices based technologies by specialty chemicals industry is (at the most) slow. The hype surrounding micro-reactors was followed a period of disillusionment. This note highlights the need to look beyond micro-reactors and micro-devices for realizing process intensification in specialty chemicals industry. The note outlines a new effort based on MAGIC (modular, agile, intensified and continuous) processes and plants. It also highlights the need for involving industry as well as large number of students (chemical engineering and process chemistry) in this ambitious program of MAGICally transforming the way specialty chemicals are manufactured.

1. Background

Specialty chemical industry forms the backbone of industrial and agricultural development of India. It caters to several key applications required for maintaining and enhancing quality of life and is going to be increasingly important for India. To fulfill the demands for addressing hitherto unmet and ever growing needs as well as expectations of a rapidly developing India, the specialty chemicals sector is expected to grow at a faster rate than the rate of growth of overall chemical industry which in turn is expected to grow faster than Indian economy (see Figure 1).

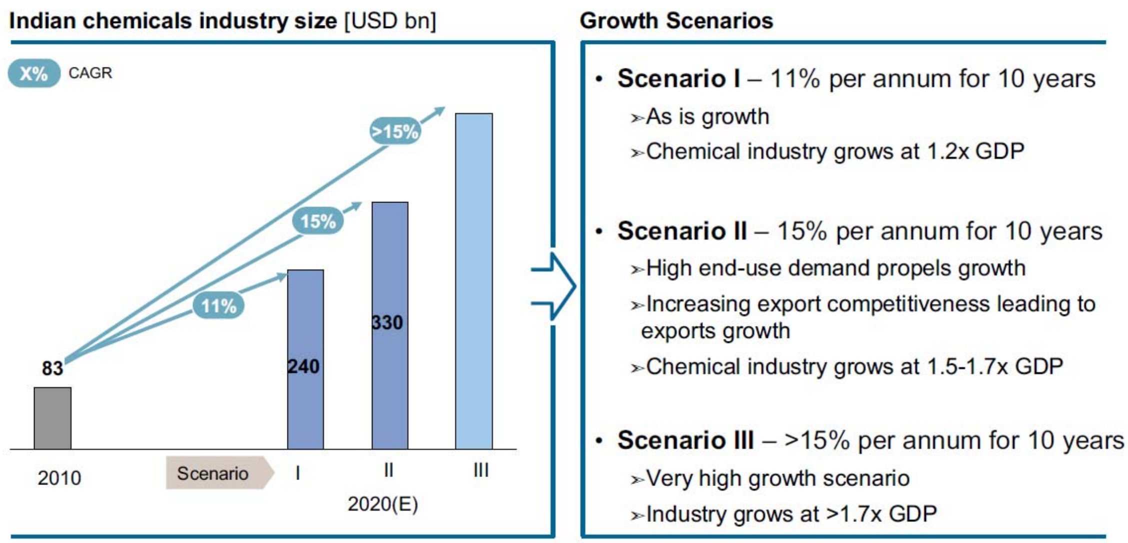

Figure 1: Adapted from Kadakia (2011)

The current turnover of Indian specialty & knowledge chemical industry is about Rs 150000 Crores (Lohokare, 2010). Even if the rate of growth of specialty chemicals sectors is assumed to be the same as the projected growth rate of overall chemical industry, the turnover of specialty chemicals sector will grow to about Rs 750000 Crores by year 2022. Such a dramatic growth cannot be realized in practice without significant science and technology interventions. It is equally essential to ensure that the industry operates in a sustainable manner by significantly reducing its impact on environment while realizing such a dramatic growth. It is essential to catch up with and exceed the global benchmarks on sustainability. The sheer magnitude of expansion, addition of turnover of Rs 600000 Crores in coming ten years and increasing demands on sustainability require tremendous research and technology inputs to support and to realize this expected growth. It is imperative that scientists and technologists conceive and undertake large and effective research programs to make the best use of this opportunity for truly bringing Indian specialty chemical industry on global map while meeting the needs of enhanced quality of life for developing India.

Indian specialty chemical industry faces many challenges today. It is interesting to note that the manufacturing and processing of chemicals have begun in early 19th century with the laboratory synthesis of urea, the methods and devices have remained largely the same. Most of the specialty chemicals are still manufactured in stirred batch reactors (devised centuries ago) operated as batch or semi-batch processes. A paradigm shift is necessary to transform this into new age, efficient and continuous plants. This article explores possibility of developing MAGIC (modular, agile, intensified and continuous) processes and plants by harnessing recent advances in process intensification for such transformation of Indian specialty chemicals industry. Some aspects of process intensification and assessment of the state of the art is first discussed. Some suggestions and challenges in developing MAGIC processes and plants are then outlined. The purpose is to provoke discussion and invite suggestions for MAGICally transform Indian specialty chemicals industry.

2. Process intensification

Process intensification (PI) may be broadly defined as the ability to obtain better results in terms of purity, selectivity and yield of the desired product by manipulating rates of relevant transport processes so as to enhance process performance (more throughput, better quality, less energy consumption, less waste, safer …). This usually translates into a reduced cost, which has been the main driver behind PI. PI therefore in a sense is intrinsic to better chemical and process engineering and has been used in practice. The new advances in intensified devices including micro-reactors and micro-fluidic devices have created significant hype and awareness about PI in recent decades.

In last decade, several research groups in Universities as well as industries have initiated research on process intensification. Many books and monographs on this area have been published besides hundreds of research papers. Some of the key large programs and consortiums in the relevant area are listed in the following table.

Table 1: Key research programs and consortiums in the area of process intensification

Program	Title/ brief description (mainly sources from respective websites)	Year
MicroChemTec	Consortium by DECHEMA for developing microreactors for commercial manufacture of fine and specialty chemicals.	2001
MCPT	Micro chemical process technology (Japan): Funded by the Ministry of Economy, Trade and Industry (METI) and NEDO (New Energy and Industrial Technology Development Organization). 31 industrial and 14 institutes are partners in this project.	2004-10
TOPCOMBI	Towards Optimized Chemical Processes and New Materials by Combinatorial Science: Utilizes high throughput and miniaturization methodologies for developing alternative catalytic synthesis routes answering demands in chemical production.	2005
NEPUMUC	The New Eco-efficient Industrial Process Using Microstructured Unit Components (NEPUMUC) program develops special microreaction equipment to perform highly exothermic nitration reactions under special safety and environmental friendly conditions. 34 members from pharma, fabricators, pilot plant suppliers and designers.	2005
BMBF Consortia	The program is focused on the use of microprocess technology for industrial production. Focus on five projects on industrial photochemistry, process intensification, polycondensation and the production of pharmaceutical intermediates in micro reactors. Aims at developing guidelines for the industrial use of microprocess technology (µVT-GUIDE)	2005
IMPULSE	Integrated Multiscale Process Units with Locally Structured Elements. 20	2005

	partners from seven European countries are members of the IMPULSE consortium. It aims at effective, targeted integration of innovative process equipment. Besides this, Impulse goals include validated business models (distributed production, mass customisation, etc.), "teachable" generic design methodology and optimisation and decision criteria for eco–efficiency.	
F3 Factory	F³ Factory is a collaborative research programme that seeks to strengthen the technological leadership through faster, more flexible production methods. It is one of the leading projects of the European Community's Seventh Framework programs. The F³ Factory consortium is made up of 25 leading companies and research institutions from nine EU Member states to collaborate on new technologies for process intensification and innovative new production concepts. Key applications targeted within the F³ Factory project include solvent-free polymers, innovative surfactants, compounds for the healthcare industry and materials from renewable resources.	2007 – 2013
COPYRIDE	COPIRIDE is an EU-project that focuses on developing new technologies, processes and manufacturing concepts for the "plant of the future" for the Chemical Industry. COPIRIDE stands for **Co**mbining **P**rocess **I**ntensification-driven Manufacture of Microstructured **R**eactors and Process Design regarding to **I**ndustrial **D**imensions and **E**nvironment. The ultimate ambition of COPIRIDE is to develop a modular production and factory concept for the chemical industry using adaptable plants with flexible output.	2007 – 2013
PILLS	Process intensification methodolgies for liquid-liquid systems in structured equipment. This project has the objective to develop and validate a design methodology & criteria for dealing with two-phase liquid/liquid-reactions leading to a new generation of flexible and high-performance process equipment (micro through to meso structured) for continuous manufacturing.	2009
Provide!	Process Intensification Development Centre (TNO, Delft)	Nov 2011
CARENA	Catalytic reactors based on new materials. CARENA promotes catalytic membrane reactors. The project aims on the activation of three specific primary feedstocks: CH_4, C_3H_8 and CO_2.	June 2011
Indus CPI/ CμR	Industry consortium on process intensification (Indus CPI) at CSIR-NCL. This was preceded by the industrial consortium on microreaction technology (CμR) was started in 2007. The consortium is aimed at identifying requirements of Indian specialty chemicals industry and undertakes development of appropriate technologies to satisfy these requirements. Currently there are ten industry members. The membership is open and being expanded.	2007/ 2011

Several research institutes and universities throughout the world have programs based on continuous flow synthesis and manufacturing at various levels. Some of these have made significant contributions in terms of devices, processes, protocols and technologies. Several papers have been published which cover a wide area of research including:

- Devices for process intensification
- Applications of these devices for continuous flow processes
- Design and scale-up/ number-up methods for process intensification

Some of the key equipment suppliers and consulting companies in the area of process intensification are listed in the following table:

Table 2: List of key industries providing products and services in process intensification

IMM (Germany)	Partially funded by the German Govt. Pioneer in metal and polymer microreactors. The focus is on translating the lab scale chemistries and allied application areas (viz. fuel cells, catalyst coating, etc.) into practice using in-house designed and fabricated microreactors & intensified process equipment.
BTS/ Ehrfeld (Germany)	Arm of Bayer Technology Services and largely caters to the in-house requirements of Bayer Ltd. However they are also driving the bigger project F3 Factory to leverage their expertise and generate a base in the fine and specialty chemicals industry in Europe.
Corning (France)	Corning is involved in making glass based flow reactors with the aim to translate the flow reactors into actual large scale manufacturing of chemicals.
Syrris (UK), VapourTec (UK), UniqSys (UK), FutureChemistry (The Netherlands)	All of these relatively smaller players fall in the category of automated synthesis platform. FutureChemistry is a facility for screening of reactions/processes using microreactors. It comprises of components/devices from different suppliers at different scales.
Little Things Factory (Germany)	Exclusively supplies glass microreactors for lab scale to pilot scale capacity.
Velocys (USA)	Velocys have developed process technologies for GTL/ FT synthesis and few other cases.
BHR Group (UK), Tridiagonal Solutions (India)	Provides consulting services and customized products for process intensification

Besides these there are few other companies either supplying intensified process equipment or process technologies based on these equipment [for example, Udhe, Degussa (now, Evonik), UOP, Siemens, MicroInnova, Thales Nano and so on].

Despite significant hype and research work, the adaption of these micro-devices based technologies by specialty chemicals industry is slow. The hype surrounding micro-reactors was followed a period of disillusionment. Our assessment of the current status of the technology is shown in Figure 2 with the help of a classical Hype cycle curve (originally proposed by Gartner Inc.):

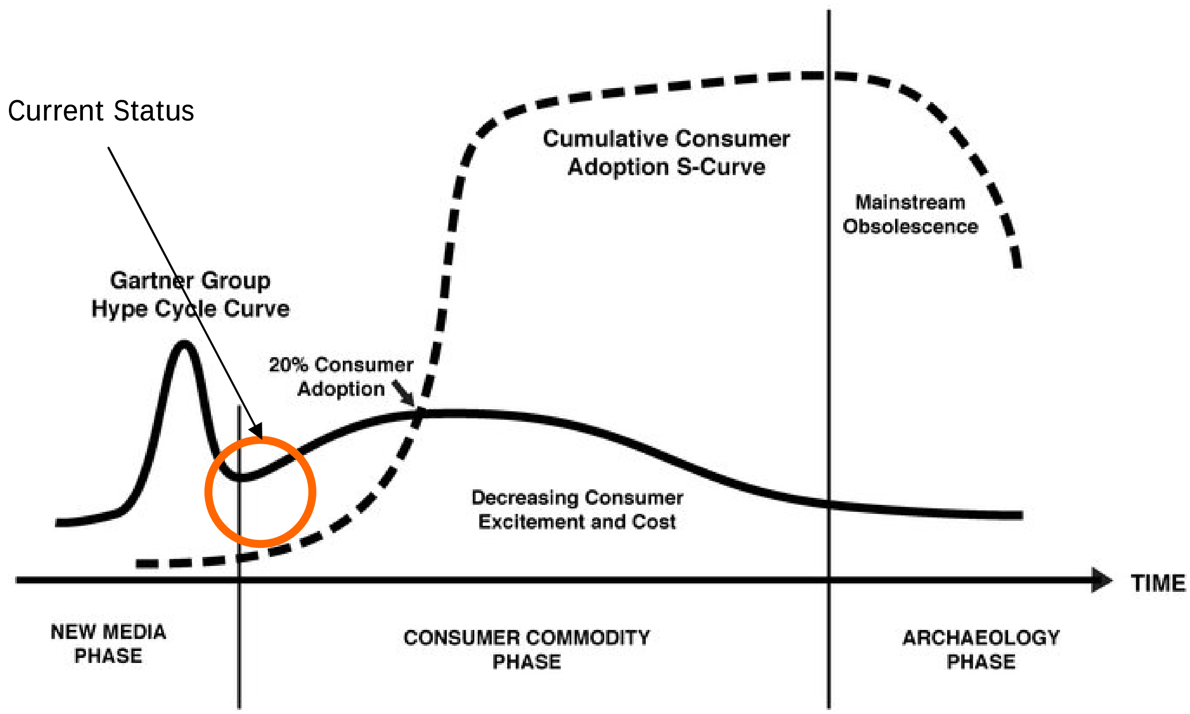

Figure 2: Background figure taken from http://mediacartographies.blogspot.in/2010/07/zombie-media-on-art-methods-and-media.html. The marked circular region is based on our assessment of the current global technology status.

The limitations and strengths of process intensification technologies and continuous processing are now better realized by researchers and practicing engineers. This is leading to more enlightened use and research plans for enhancing the adoption and relevant development of process intensification technology. The gradual but certain expansion of scope of research and development from micro-devices to milli or even centi-scale devices is rapidly enhancing potential for adoption in practice.

It is important at this juncture to focus on the following key components to truly harness the technology:

- Modular nature of devices: modular nature of devices and process equipment will significantly reduce field work and will shrink the time for translating laboratory research to practice. It is essential to develop new types of modular devices and develop standards as well as inter-operability policies for assisting development of new and better modular devices
- Ability to adopt process changes: rapid changes in the market requirements demand a step change in ability of process plant to reconfigure and adapt to the market requirements. New research and design methodologies are needed for this purpose.
- Intensified transport processes: Despite significant research on development of intensified process equipment, further research and focus on developing intensified processes is needed to incorporate some of the learning (causes for the disillusionment) of the last decade.

- Continuous processes: it is essential to harness advantages of continuous processing without significantly loosing the advantages of batch (like flexibility and multi-product ability) processes.

Based on these concepts, a large research program entitled Indus MAGIC (Innovate, develop and up-scale MAGIC (modular, agile, intensified and continuous) processes and plants by chemical cluster laboratories of CSIR. The key MAGIC concepts are briefly outlined in the following.

3. MAGIC processes and plants

MAGIC processes and plants are based on using variety of new concepts and technologies to transform specialty chemicals industry (some of which are listed in the following table):

Table 3: Key differences in conventional and MAGIC processes/ plants for specialty chemicals

Conventional way	**MAGIC way**
Batch or semi-batch processes	Continuous processes
Stirred reactors	Compact, intensified reactors
Less flexible plants, clumsy cleaning	Modular, agile and reconfigurable plants
Use of stoichiometric reagents	Use of catalysts & catalytic processes
Generate significant waste per unit product	Intensified processes/ operation to maximize atom efficiency
Large water foot print	Reduced water foot print via water recycle and reuse
Use hazardous solvents	Conduct reactions in water/ benign solvents
Reactions limited by transport limitations	Reactions at intrinsic rates without any transport limitations
Separate unit operations: reactors, separations	Integrated processes with multi-functional reactors/ process equipment
Cabled process instrumentation & control	Wireless process instrumentation & control/ new paradigms for process optimization

Modular, agile, intensified and continuous concepts underlying MAGIC processes and plants are briefly discussed in the following.

Modular: Modular process equipment by definition comprise of interchangeable modules containing groups of equipment with pre-defined interfaces to utilities etc. Such modules with standardized interfaces will significantly reduce field work and will reduce time from lab to practice. It will facilitate shorter schedules, compact design & rigorous testing which will result in enhanced flexibility. However, it is essential to develop standards for interfaces and new interoperability policies. It is also necessary to develop better concepts in modularizing including new connectors for variety of conventional and intensified compact process equipment.

Agile: Agility is related to an ability to change process plants quickly in response to market needs and to manufacture multiple products. This attribute essentially demands re-configurable process and plant designs and dynamic plant layout. This will need development of new design paradigms based on ranges instead of point values as input parameters to the design process. Wireless technologies need to be harnessed for process instrumentation and control which will be enabler for quick re-configuration and dynamic layout. Recent advances in combinatorial methods to scan the space consisting of design variables and process functions need to be deployed for designing desired agile plants.

Intensified process/ process equipment: This involves making use of enhanced transport rates to realize reactions with intrinsic rates. Intensified processes and process equipment employ tricks to realize very large surface area to volume ratio and orders of magnitude large interfacial interactions to facilitate significantly faster mixing, heat transfer and mass transfer rates. Such equipment will require much smaller reaction volumes and therefore low inventories and intrinsically safer operations.

Continuous: Converting conventional batch processes of specialty chemicals to continuous one will lead to compact plants requiring significantly lower inventories. This will make such plants intrinsically safer and with lower environmental footprint. Besides this, usual advantages of continuous processes like consistency in product quality, better control on selectivity, better atom efficiency and more efficient use of utilities can be realized in the MAGIC processes and plants.

There are several challenges in realizing this dream of MAGICally transforming the way specialty chemicals are manufactured. Some of these are technical and even more difficult ones are non-technical. Key technical or scientific challenges can be summarized as:

- Early stage reaction engineering analysis for quantifying potential of process intensification for a given process chemistry: this is a crucial step which provides guidelines for further steps and often determines which route is to be followed for potential intensification. It will be useful to carry out basic reaction analysis to variety of chemistry platforms (see for example, analysis presented by Calabrese and Pissavini [2011] on nitration and hydrogenation reactions).
- New concepts & designs for intensified process equipment/ process control: It is essential to harness state of the art computational and experimental tools to ensure that materials and energy are delivered at right time and at right place. This will ensure realization of best possible intensified process equipment. A new paradigm is needed to evolve appropriate design & process control strategies.
- Integrating multiple process steps intensified with different approaches on a unified platform: New ideas and new approaches are needed to implement ‘systems approach’ and to carry out ‘systems optimization’ for the entire process flow sheet when different intensification strategies are used for different steps.
- Managing issues beyond reactions: Several issues like flow distribution during numbering-up, corrosion, erosion, clogging, maintenance, cleaning and reconfiguration become crucial while translating process intensification ideas from laboratory to practice.

The associated non-technical challenges may be outlined as:

- Changing mind set of specialty chemicals industry (which in India is mostly family owned rather than publically listed): need to educate industry doyens and illustrate advantages of MAGIC processes by real life examples. A series of focused workshop may be helpful in this regard.

- Bringing down costs of MAGIC processes and plants to ensure acceptable return on investments (RoI): This requires so called Gandhian innovation or more from less for more principles (Mashelkar, 2011).
- Reducing risks associated with new technologies like MAGIC plants and processes: It will be useful to explore new models of public-private partnerships so that magnitude of risk is within acceptable limit.
- Bringing together critical mass of scientists, process technologists, chemical engineers and industrialist to make an impact on specialty chemicals sector

It is essential to put together a large research program to address and overcome these challenges. The MAGIC concepts outlined here need to be developed differently in light of the current status of Indian specialty chemicals industry than the prevailing concepts in the western world. Any such research program needs to involve industries from the beginning. It is essential to create a strong relationship based on mutual trust between scientists and industry doyens. Secondly, it is also essential to involve large number of chemical engineering and process chemistry students in the program to sensitize them with the concepts of MAGIC plants and processes. These students will eventually work in the industry and will facilitate implementation of MAGIC concepts in industry and realize the desired transformation of the way we manufacture specialty chemicals today. The Indus MAGIC program formulated by CSIR chemical cluster laboratories is aimed as a first step towards it (Ranade and Lakshmikantam, 2012). The overall structure of the program is shown in the following:

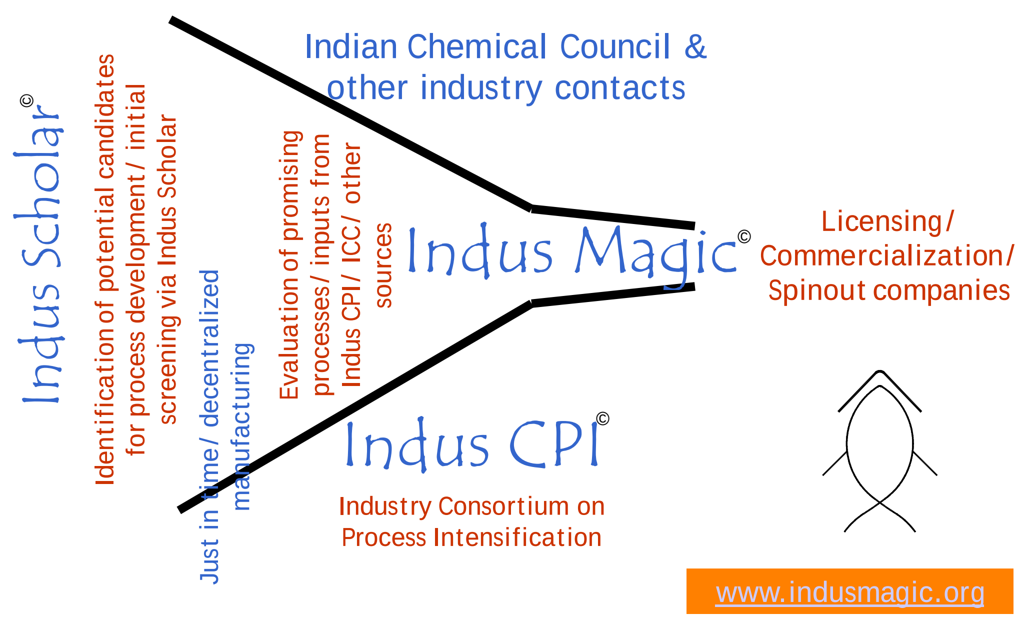

Figure 3: Structure of Indus MAGIC program of CSIR Chemical Cluster Laboratories

The proposed Indus MAGIC program for the first time brings together chemists and chemical engineers together to work on a large canvas relevant to Indian specialty chemicals sector involving atom efficient process routes (better catalysts, benign reactants and solvents) and enhance product yield and quality. The modular, agile, intensified and continuous (MAGIC) chemical plant facility will be established so that developed technologies and processes can be demonstrated on a scale of interest to industries. Wireless technologies will be harnessed to develop new ways of designing reconfigurable plants. The MAGIC plants will show case futuristic, new age and sustainable specialty chemical industry. The industry consortium on process intensification (Indus CPI) and a student's program on specialty chemicals oriented laboratory projects (Indus Scholar) will be associated with Indus MAGIC. A close interaction with industry organizations is also planned.

Based on a critical analysis of existing strengths and inputs about the industry needs, the research proposed in Indus MAGIC is aimed at addressing following areas:

- Convert batch processes to continuous processes
- Process intensification by carrying out reactions at high T and P
- Develop catalytic processes preferably in benign solvents/reagents
- Develop multifunctional reactors/ process equipment
- Develop better crystallization, filtration and drying process equipment
- Develop new hybrid technologies for water recycle and reuse

Several work elements proposed in this program have direct applications and significant market prospects and will benefit specialty chemicals sector. Broadly these applications and market prospects can be grouped into two parts:

- Process technologies and basic engineering packages: There are several work elements focusing on development of specific processes. The proposed work will develop new routes/ catalysts/ better engineering to develop competitive process technologies. The specific cases included in this program are selected based on preliminary techno-economic analysis by the proposers. Some of these are also selected based on specific leads provided by the industry contacts and based on information about specific interests expressed by some of the industries. Once the concepts are proven at the laboratory level under the Indus MAGIC, the further work of translation to practice may be taken up as bilateral projects with client industries.
- Process equipment, hardware and software products: Several new ideas for realizing compact, modular and intensified process equipment in this project. Some of these will lead to promising hardware products with commercial impact. Efforts will be made to identify such potential. Relationship with some of the process equipment manufacturers will be established which will be useful for this purpose. Some of the modeling work proposed in this project may lead to useful tools. Efforts will be made to exploit commercial applications of these tools. Efforts will also be made to explore option of releasing open source versions of these tools to enhance the visibility and impact on research on process intensification.

We believe that the Indus MAGIC program has a potential to avoid pitfalls of pushing micro-reactor technology into specialty chemicals sector. The program is expected to provide solutions appropriate to Indian context and able to transform the way specialty chemicals are manufactured in India.

4. Conclusions

It is essential to learn from previous efforts of pushing micro-reactor technology to specialty chemicals section and formulate a research program to develop solutions appropriate to Indian context. The Indus MAGIC research program proposed by CSIR chemical cluster laboratories targets development of new ways of designing process equipment and their integration with process chemistry to realize atom efficient (creating less waste products per kg of desired product), environmentally benign and globally competitive processes and technologies. The focus is on developing effective solutions for specialty and fine chemicals sector based on MAGIC (modular, agile, intensified and continuous) concepts. This sector caters to several key applications required for maintaining and enhancing quality of life and is going to be increasingly important for India. The specialty chemicals sector is expected to grow at nearly double the rate of growth of overall economy to fulfill the demands for addressing hitherto unmet and ever growing needs as well as expectations of a rapidly developing India. These new opportunities, the sheer magnitude of projected expansion and increasing demands on sustainability require tremendous research and technology inputs to support and to realize this expected growth. This Indus MAGIC research program is planned to meet these needs and to facilitate transformation of Indian specialty chemical industry.

Acknowledgement

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