Integration of Fundamental Research Into Undergraduate Classrooms

Jerry K. Keska

College of Engineering,
University of Louisiana
Lafayette, LA 70506

Abstract

Currently, there has been an increasing emphasis on the performance of students in engineering curricula. This has resulted in a considerable amount of research being done to analyze the performance of students in engineering, particularly at the freshman and sophomore levels. The principal objective of these research efforts has been to determine factors that may influence students in their decisions on whether or not to pursue an engineering education, or to try something different. In discovering these critical factors, researchers are hopeful of success in making the engineering education experience a more enjoyable and less monotonous one for students, thereby improving retention in engineering programs and ensuring later success. In the undergraduate teaching process, instructors and students alike often get bored solving simple, rather limited, classic textbook problems which require little if any imaginative thinking. To increase student interest and creative hands-on problem-solving skills, an innovative approach is needed that pushes students to their creative limits through the use of open-ended projects in which realistic, complex, challenging state-of-the-art problems are investigated. This new approach will increase student enthusiasm and provide closer alignment of classroom topics with today’s standard industry practice.

This paper will deal with a unique application of the research/teaching method used at the undergraduate level, using a hands-on laboratory approach in conjunction with classroom lecture. The approach can be tailored to all levels from introductory freshman to senior-level classes. An open-ended project is utilized, requiring a creative approach for its solution. In this way, a full-cycle learning experience is realized, through development of an initial idea through the design and construction of a prototype and with the application of feasibility.

Introduction

One of the key issues, which significantly determines our tools and approach to any problem, is the determination of a process character, if it has a random or deterministic nature, or more realistic, the determination of the composition grade of both components and their significance in the phenomenon composition. Probably the following citation of Heinz Pagel, gives us an important clarification “The randomness at the foundation of the material world does not mean that knowledge is impossible or that physics has failed. To the contrary, the discovery of the indeterminate universe is a triumph of modern physics and opens a new vision of nature.” In this matter one may argue successfully about a factual basis of a hypothesis that such general classification of processes for random or deterministic or predictable or unpredictable are rather a matter of perception, level of analytical depth, adequacy of the model applied, accuracy and completeness of observations used, the level of involved errors and verification process and/or other subjective correlation between dependant and independent variables or a combination of all the above mentioned components, rather than the character of the process itself. In other words, a purely random process, classified as a black box phenomenon from ones perception, could be fully deterministic from the perception of another person who may already know a deterministic model and is fully predictable, based on the known correlations. In addition to this controversy, this fact requires development of a list of challenging problems that need to be solved. In this sense a challenging problem is defined as a problem that is not yet solved satisfactorily and results could not be predicted with
required accuracy (e.g. not ready-off-shelf instrument/system/solution is available and a solution is not known not only to the students but also to the professor).

One example of such a problem is the process of flow pattern recognition in two-phase flow, which currently is considered widely as a random (unpredictable) process and has continuously challenged the academic community since the 1940s. This problem is generating a group of especially challenging subjects for open-ended projects for both graduate and undergraduate courses. In this case, as in any experimental approach, the weight of such concepts such as uncertainty, error analysis, and data verification and identification, can never be underestimated.  

Due to the complexity of “real-world” problems as illustrated by the above examples, there is broad agreement in the academic and industrial research communities that the learning process in these areas is a lifelong perpetual procedure wherein subjects (technical focus) and tools are changing constantly. The importance of exposing students to all possible scenarios in approaching deterministic or random processes, especially where the complexity of the problem involves superposition of both deterministic and random procedures, is therefore paramount. Successful students must have the knowledge and confidence of how to approach such complex problems, to dissect, analyze and then synthesize the problem, and to intelligently interpret and validate the results obtained.

### Teaching by Inquiry

It is common knowledge that engineering is a challenging field of study and requires considerable dedication and effort on the part of students to successfully complete the degree requirements. However, it would be grossly incorrect to say that engineering is an excessively tedious field of study, with no bright career opportunities. In an attempt to increase student interest and ability in creative hands-on problem solving skills, an application of research and teaching by inquiry approach is introduced in the undergraduate level classes. In these classes, an open-ended project vehicle is used in which problems to be solved are intended to be realistic and complex, state-of-the-art and challenging, to generate and intensify the enthusiasm of the students and to more substantially prepare them for the “outside” world. It is crucial that the students need to understand their participation in the discovery process where they need to be active participants, not only passive receivers. In such processes, faculty members and students are simultaneously learners and investigators, whose communications support a more effective learning process and generate benefits for both.

One of the preliminary requirements for successful implementation of these processes is to make appropriate choices of good quality references used, such resources are patents, refereed papers and reports, and electronic databases via the library or the Internet. In the selection of resources, two key issues are important: (1) the use of objective and accurate references, and (2) access to state-of-the-art information. Two of the most important sources of information in this case are refereed journal papers and patents. Limited subject knowledge on the part of the student, and a plethora of relatively easy-to-access scientific and mostly pseudoscientific information on the Internet, create a situation requiring the need for intense involvement of knowledgeable faculty in the teaching process. This includes defining rigorous criteria for evaluation of quality resources before use in a learning and application processes. Due to the broad spectrum of materials available on the net and their ready accessibility, there is also the ever-present danger of plagiarism. This therefore requires that the instructor explain to students the ethical and judicial repercussions, which hopefully will guide students to self-policing.  

The teaching-by-inquiry method involves defining the subject and scope of an open-ended project, in connection with the following objectives:

1. An introduction to the creative thinking process by finding a solution to a challenging problem which involves a full cycle of activities beginning with brainstorming to create alternative solutions, through design and construction of the first prototype, including a feasibility study, prototype evaluation and redesign, and finally an engineering report documenting the design, development, test and evaluation of the end product;

2. Background search for the closest related solutions to the issue (refereed journal papers, patents, and web sources and elibrary materials), which provide comparisons to the approach, implemented in the process.
3. Introduction and application of uncertainty and error analysis including an error reduction process and data validation;

4. Application of computer-aided experimentation and research processes using tools such as: Matlab, CADAS, the Internet, Lab VIEW, spreadsheets, graphics software, and other electronic data basis;

5. Prediction of the results from theory, and application of the phenomenological approach coupled with physical experimentation to verify the theory and assumptions used;

6. Application of data analysis and verification techniques (bias and precision errors, literature comparisons, concomitancy and redundancy);

7. Computer-aided communication and dissemination of results (class and conference presentations, reports and publications).

A challenging problem, in this context, is defined as a problem, which has not been solved satisfactorily on the industrial level, i.e., a ready-off-the-shelf solution is not available to students or professor. Such a problem will normally lend itself to the application of a phenomenological approach requiring a literature search, computer usage and application, utilization of random and/or deterministic analysis techniques, and compatibility for a full-cycle solution from the initial idea, through design and prototype development, feasibility/prof-of-concept, and final report with a formal presentation, followed by prototype improvement.

Examples of challenging open-ended problems well suited to the teaching by inquiry method are 4, 5, 7

(a) Spatial and temporal distribution of concentration;
(b) Flow pattern recognition;
(c) On-line viscometer;
(d) Multi-phase flow measurement systems;
(e) Wear in machinery; and
(f) MEMS (Micro-Electro-Mechanical Systems) including fluidics, two-phase flow, and micro heat exchangers.

The teaching-by-inquiry process is started by introducing students, in the shortest possible way with hands-on experience (crush-course type approach), to the following subjects:

1. How to find quality resources on the net and in the library? (including patents, refereed journal papers and reports).
2. How to approach, design and build a unique system in full cycle?
3. Experiments and experimentations, including data collection and analysis, data validation using concomitant measurements and redundancy, error and uncertainty analysis, data reduction and analysis, and results presentation.
4. Web and computer-aided applications.
5. Demonstration of a complex open-ended project including experiments, reports, papers and presentations.
6. How to plan and conduct a complex experiment.

After that, in the next step, a request for proposal is issued and collected. After teams and proposals are accepted, teams consisting of one to three students begin to work on the topic, doing a background literature search and analyses. Based on the search and analysis, teams designed their first prototype with a feasibility study program, and definition and measure the final product success. First checkpoint is the first part of each team’s report submission. If the report is accepted, it is graded and returned to students with feedback. If a report is not accepted it is also returned to students with listed deficiencies, which need to be addressed. The next step is to build a first prototype, conduct feasibility study, analyze data, write a final report, and make a presentation. The two-phase flows in mini or microchannels or micro fluidics issues are excellent examples of challenging problems for open-ended projects 10.
Two-Phase Flow

Gas and liquid flowing through a pipe/channel display a number of different spatial and temporal dynamic distributions of mixture components, which are distinguished as flow patterns\textsuperscript{1,2,3,4,5}. Although these flow patterns can be visually observed, however due to our eye properties like frequency respond and an optical transparency of majority of liquids and gases, the effective ability to use visual observations for a quantitative determination of flow patterns are severely limited and significantly limits the resolution of such observations. Plethora of independent parameters involved in the two-phase flow of heterogeneous mixture is making this process more complicated and more challenging for understanding, mathematical modeling and simulating or calculating of such parameter like the length pressure gradient. In those mathematical models for calculations and simulations, as well as for interpretation of experimental results a very complicated and random phenomenon of flow patterns need to be quantitatively and accurately incorporated thereby producing higher accuracy in calculation and description. Unfortunately, at present, a method to measure flow patterns is not available, but also not available are mathematical models with the ability to ascertain, the quantitative incorporation of flow patterns. So, it is understandable that for such case any reasonable attempt to define and incorporate quantitatively a flow pattern phenomenon in mathematical expressions is beneficial. Also, due to the significance of such parameters like the in-situ velocity and concentration/void fraction in the process of control and measurement of two-phase flow, it is logical to use those parameters for the description of flow patterns. Considerable amounts of mostly experimental work have been done in recent years to progress these flow pattern detections and their transitions from one flow pattern to another flow pattern\textsuperscript{10,11,12}. However, these attempts have not generated into fully developed solutions. Also, in many cases concerning the analysis of experimental results reported by different authors, one may observe significant differences. These differences could also be due to subjective observation and determination of flow patterns, and lack of quantitative incorporation of flow patterns into the model.

Although investigations such as those described above are useful for the particular conditions and situations described in the literature, applications of those are very limited. There still does not exist an analytical or empirical model for heterogeneous mixture flow, which incorporates quantitatively the flow patterns and covers the entire range of in-situ concentration. Even the use of visual observation of flow patterns will distinguish only five or six different kinds of flow patterns, in this extremely highly dynamic and continually, changing process\textsuperscript{1,2,3}. This area of expertise is very highly observer dependent, and it is characterized by a very low resolution. Thereby, it makes it almost impossible to compare the flow patterns from one experiment to the other. Because of the lack of such models, abilities and measure, any reasonable attempt to develop a mathematical model with the flow patterns totally focused on the specific, unique and limited conditions, will constitute a major, significant progress in the description of two-phase flow phenomena. The further and long-term progress can be achieved by further generalization of such a model, as well as by the development of an objective measure of the flow patterns using adequate measurement methodology and a measurement system with the proper capability.

For any given steady-state condition of the flow, values of pressure, mixture transparency and concentration all fluctuate as a result of the nature of the flow and physical conditions inside the microchannel. Experimental dynamic pressure and concentration signals consist of two components, an average (dc) and a fluctuating (ac) component, such that the actual concentration consists of the sum of the average and fluctuating components. In further expanding the depth of analysis of concomitancy and impact of the flow pattern on the signal, the ac signals are transformed into both the amplitude domain as the frequency of occurrence in function of concentration; and frequency domain as the power spectral density in function of frequency\textsuperscript{4,5,7,9,10,12}. By analyzing the concentration range, frequency of occurrence, and the distribution shape including “skewness,” taking all signals at the same flow conditions for both the capacitive and conductive systems, a strong similarity is noted, indicating that both the capacitive and conductive systems are concomitant with regard to concentration measurement and effects of the flow pattern for this particular experiment. In order to assess concomitancy in the entire spectrum of flow patterns, a study of such characteristics in
FIGURE 1a. In-Situ Spatial Concentration Signals in Time, Amplitude and Frequency Domains from Conductive Systems for Air-Water Mixture Flow in Microchannels.
FIGURE 1b. Voltage signals related to the interfacial phenomenon in the time, amplitude and frequency domains from optical systems for air-water mixture flow in microchannels.
FIGURE 2. PDF functions of both in-situ concentrations from capacitance and conductance sensors vs. in-situ concentration from the experiments for air-water mixture flow in microchannels.

the full range of flow pattern variation has been conducted by comparing concentration results in the time, amplitude and frequency domains for over 20 signals vs. time for evenly distributed flow pattern in the whole range of concentration from 0 to one for both capacitive and conductive systems. Due to space limitations only a few of these
measurements are presented beginning with Fig. 1a, where in the top view over 20 time traces of instantaneous concentration in 5-second time intervals for given various values of mean concentration are presented in a “waterfall” depiction for the conductive system. Transformation of these time traces into the amplitude domain in the middle part of Fig.1a yields a waterfall characteristic of PDF vs. concentration for given mean values of concentration. With gradually increasing mean values of concentration from “gas only” to “water only,” it is a gradual change in dominance from all gas to pure water is noted, as distinguished by the location of the single peak. These changes occur gradually, with the all-vapor left-side peak, to two-sided peaks, and finally to the all-liquid right-side peak, for concentrations greater than 50%. In a direct comparison of both capacitive and conductive systems, it is useful to compare characteristics for both systems as illustrated in Fig. 2, where the PDF functions for both systems are nearly identical. Additionally, a plot of RMS values vs. concentration for both systems is illustrated in Figs. 3. These plots verify the concomitancy of both systems in terms of concentration, and their sensitivity to flow patterns.

FIGURE 3. RMS values of both in-situ concentrations from conductance and differential pressure vs. the RMS value of in-situ concentration from the experiments for air-water mixture flow in microchannels.

More information about the concomitancy of two concentration signals is obtained by comparing deviation of the RMS concentration values measured by both systems for the same time and space.

The RMS values of the in-situ spatial concentration from both capacitive and conductive systems vs. in-situ spatial concentration are shown in Fig. 3. As illustrated in Fig. 3, both RMS curves of concentration from capacitive and conductive systems are very similar and the curves almost overlap. An even better appreciation of the differences between RMS pairs can be developed by analyzing the relative deviation of RMS values of concentration over the concentration range of the experiments.

TWO-PHASE FLOW MODEL

Assuming one-dimensional flow and a constant pressure gradient, the pressure drop in a channel/conduit can be expressed by the equation:

\[ \Delta P = \frac{dP}{dL} \Delta L \]  

(1)
Where \( P \) is the pressure of the two-phase mixture, \( \frac{dP}{dL} \) is the pressure gradient in the channel/conduit and \( L \) is the channel/conduit length. The total pressure gradient can be seen as a superposition of three components due to the mixture acceleration, the friction and gravity. This is shown in the following equation:

\[
\frac{dP}{dL} = \frac{dP}{dL}_a + \frac{dP}{dL}_f + \frac{dP}{dL}_g.
\]  
(2)

For steady-state conditions and for small and moderate pressure differences for a horizontal or short vertical channel/conduit, the total pressure gradient is due to frictional pressure gradient as:

\[
\frac{dP}{dL} = \frac{dP}{dL}_f.
\]  
(3)

The frictional pressure gradient of a two-phase mixture can be viewed as a superposition of two separate frictional pressure gradients due to the gas component and liquid component as:

\[
\frac{dP}{dL}_m = \frac{dP}{dL}_l + \frac{dP}{dL}_g.
\]  
(4)

Where for steady-state flow conditions and homogenous spatial and temporal distribution of phases in the mixture with the in-situ overall spatial concentration \( c_v \), the frictional pressure loss (theoretical) of the mixture is:

\[
\Delta P_{\text{theoretical}} = \frac{dP}{dL} \Delta L = \frac{4L}{2D} \left[ \frac{f g}{g} \rho_l \left( 1 - c_v \right) + f_l \rho_l c_v \right].
\]  
(5)

The friction factors could be determined for liquid and gas respectively by using the laminar flow regime which is the equation \( f = \frac{64}{Re} \) or for turbulent flow the Colebrook equation or direct numerical values obtained from Moody diagram [26] for given \( Re \) and \( \frac{\varepsilon}{D} \) as:

\[
\frac{1}{f^{\frac{1}{2}}} = -2.0 \log_{10} \left[ \frac{2.51}{f^{\frac{1}{2}} \cdot \text{Re}} + \frac{\varepsilon}{D} \right] + \frac{18}{3.7}
\]  
(6)

Where \( Re \) is the Reynolds number of the gas or liquid flow calculated separately for in-situ conditions:

\[
Re = \frac{vDP}{\mu}.
\]  
(7)

Because the pressure drop is proportional to the amount of energy consumed by the mixture flow, in the three-dimensional system, this correlation can be represented by a surface with a uniform distribution of concentrations in the mixture. For those ideal conditions, the theoretical pressure drop can be expressed with velocities of each phase and in-situ concentrations as follows:

\[
\Delta P_{\text{theoretical}} = \frac{dP}{dL} \Delta L = \frac{4L}{2D} \left[ \frac{f g}{g} \rho_l \left( 1 - c_v \right) + f_l \rho_l c_v \right].
\]  
(8)
And for length pressure gradient as:

\[
\left(\frac{\Delta P}{\Delta L}\right)_{\text{theoretical}} = \frac{1}{2D} \left[ f_g v^2 g (1-c_v) + f_l v^2 l^2 \rho_l c_v \right]
\]  

(9)

If compare the experimental results of pressure gradients, theoretical pressure gradients (calculated by eq. 9), and flow conditions for given in-situ concentrations and velocities, and flow patterns, not surprisingly, there are noticeable significant differences between theoretical and experimental gradients. The differences are very significant (100% and higher) and therefore, these calls for a significant modification of this model by the incorporation of another flow related independent parameter. A phenomenon that is completely ignored in the equation (9) is the flow pattern phenomenon. This phenomenon impact varies in the data and, it is not incorporated into the previous model and this important impact is widely recognized in literature [1, 2, 3, 6]. At this point, it is beneficial to further explore the incorporation of the flow pattern phenomenon in the form of a flow pattern coefficient, where the length pressure gradient for given conditions becomes a function of in-situ component velocities, constants, frictions coefficients, in-situ concentration, and flow pattern coefficient (Fp) and the differences between the theoretical and experimental values would be reduced significantly, which yields:

\[
\left(\frac{\Delta P}{\Delta L}\right)_{\text{tested}} = \frac{1}{2D} \left[ f_g v^2 g (1-c_v) + f_l v^2 l^2 \rho_l c_v \right] Fp
\]  

(10)

By combining the equations, (9) and (10), the combination will produce:

\[
\left(\frac{\Delta P}{\Delta L}\right)_{\text{tested}} = \left(\frac{\Delta P}{\Delta L}\right)_{\text{theoretical}} Fp
\]  

(11)

Therefore, the value of flow pattern coefficient (Fp) can be defined as follows:

\[
Fp = \frac{\left(\frac{\Delta P}{\Delta L}\right)_{\text{tested}}}{\left(\frac{\Delta P}{\Delta L}\right)_{\text{theoretical}}}
\]  

(12)

This equation defines the flow pattern coefficient, which obviously is not a constant and is a dimensionless factor. Experiments justified the assumption that Fp is also at least a function of velocity and in-situ concentration.

The use of dimensional and similitude analysis is helpful for a better understanding of the internal structure of Fp and development of the model. At least a homogenous two-phase mixture flow in a close channel is directly related to the single-phase flow. In single-phase closed channel flow, viscous force is dominant if the channel is horizontal, where the Reynolds number is critical. Imaging that the two-phase mixture flow is composed of the two single-phase streams; one is either the liquid or the gas, and it flows inside the channel as mainstream; the second is the other phase fluid, and it flows inside the mainstream. The mainstream embraces the other flow so that it can be considered as “a closed channel” for the other fluid. The other fluid flows inside the mainstream so that we name it as inner-stream. For a steady-state mixture flow of gas and liquid, they both dynamically interfere with each other, and therefore the end result can possibly produce:

\[
Fp = \left(\frac{\nu}{V} \right) c_1 \left(\frac{1-c}{c_v} \right) c_2 \left(\frac{L}{v} \right) c_3 \left(\frac{v}{g} \right) c_4
\]  

(13)
Size and shape of the channel or properties of the mixture components do not limit this definition. For the experiment, the gas in the mixture is air, whereas the liquid is water. Both fluids are chemical stable, although its concentration may change. The pressure gradient is insignificant for causing kinetic viscosity to change, and both viscosities are considered constant. Therefore, Eq.13 can be simplified to:

\[ F_p = \left( \frac{v}{w} \right)^{c_1} \left( \frac{1 - c}{c_v} \right)^{c_2} \exp(c_3) \]  

(14)

And further to:

\[ \ln(F_p) = c_1 \ln\left( \frac{v}{w} \right) + c_2 \ln\left( \frac{1 - c}{c_v} \right) + c_3 \]  

(15)

For the experimental data using the best-fit criterion in multiple regression analysis, the coefficients \( c_1, c_2 \) and \( c_3 \) were calculated, generating the following correlation:

\[ \ln(F_p) = 11.3 - 2.88 \ln\left( \frac{v}{w} \right) + 2.33 \ln\left( \frac{1 - c}{c_v} \right) \]  

(16)

To validate the regression, two statistical properties are calculated one is the multiple correlation coefficient, which shows the general goodness of curve fitting and is equal 0.963. In general, the higher the value (it is always smaller than 1), the better the regression fits the experimental points. The other is the standard deviation equal 0.4114 what it strongly indicates that there is a significant correlation among the flow pattern coefficient, concentration, velocity and the pressure drop. The flow pattern coefficient equation in a power form is as follows:

\[ F_p = \exp(11.3)\left( \frac{v}{w} \right)^{-2.88} \left( \frac{1 - c}{c_v} \right)^{2.33} \]  

(17)

Using the newly determined algorithm for flow pattern coefficient (Eq. 17) by combining with Eq.10, the values of the calculated pressure drop were calculated. After the application of the flow pattern coefficient, the overall sum pertaining to the squares of errors drops from 6549.231 to 190.016, which indicates a significant improvement of 83% in the accuracy. This shows a significant reduction of differences between theoretical and tested values of pressure drop by using the coefficient of flow patterns.

**Nomenclature**

\[ A, c, k \quad - \text{Constant value, cross sectional area, unique experimental constant, coefficient} \]

\[ c_v \quad - \text{In-situ volumetric spatial concentration, } c_v = \frac{V_i}{V_m} \]

\[ C \quad - \text{capacitance (F)} \]

\[ \text{CADAS} \quad - \text{computer aided data acquisition system} \]

\[ \text{CPDF} \quad - \text{cumulative probability density} \]

\[ \text{CPSD} \quad - \text{cumulative power spectral density} \]

\[ R \quad - \text{resistance (} \Omega \text{)} \]

\[ G \quad - \text{conductance (} \mu \text{S)} \]

\[ \text{AC} \quad - \text{fluctuating component of the signal (-)} \]

\[ D_{p/DL} \quad - \text{Pressure drop} \]

\[ D \quad - \text{Pipe/channel diameter} \]

\[ F_p \quad - \text{Flow pattern coefficient} \]

\[ g \quad - \text{Gravitational acceleration} \]

\[ L \quad - \text{Length} \]
\( \dot{M} \) - Mass flow rate
\( p \) - Pressure
\( \Delta p \) - Pressure drop
\( Q \) - Volume flow rate
Opt. - optical
\( P \) - Pressure (Pa)
PDF - probability density function
PSD - power spectral density
RMS - root-mean square value of the signal
\( V \) - Voltage (V)
\( Q \) - Volume flow rate (m\(^3\)/s)
Re - Reynolds number
\( V \) - Volume
\( v \) - In-situ velocity
\( v_w \) - In-situ water velocity, \( v_w = \frac{Q_w}{c_v A} \)
\( v_{w,s} \) - Superficial water velocity, \( v_{w,s} = \frac{Q_w}{A} \)
\( T \) - Observation time, average time
\( t \) - Time variable
\( \rho \) - Density
\( \mu \) - Viscosity
\( v_g \) - Kinetic viscosity of gas
\( v_l \) - Kinetic viscosity of liquid

Subscripts
\( a \) - Air, acceleration
\( f \) - Friction
\( g \) - Gas, gravity
\( m \) - Mixture
\( l \) - Liquid
\( v \) - Volumetric
\( s \) - Superficial
\( w \) - Water
\( I, II, III \) - First, second, third type
\( 1, 2, ..., i \) - 1st, 2nd, ..., i-th component or value

References


Dr. Keska, a mechanical engineer at the University of Louisiana at Lafayette, currently serves as an Associate Professor of Fluid Power and Mechanical Systems in the Industrial Technology Department of the College of Engineering, and he is a Graduate Faculty member in the Department of Mechanical Engineering. His research interests are in the areas of Micro-Electro-Mechanical Systems (MEMS), fluid dynamics of complex heterogeneous mixtures (multiphase, slurries), tribology, micro heat exchangers, computer-aided measurement systems and instrumentation, electromagnetic sensors, turbulence and flow pattern phenomena in mixtures, and deterministic and random signal analysis processing and validation.