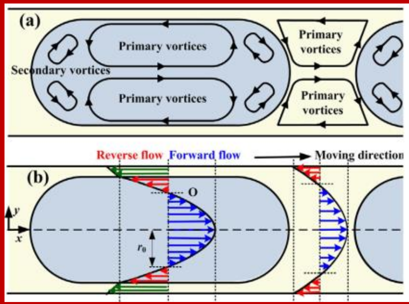

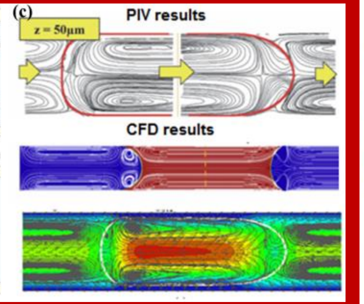

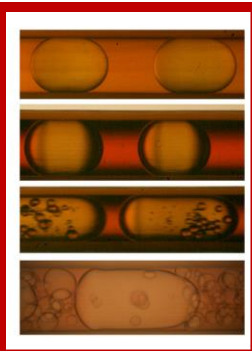

Prof. Rufat Abiev is a Full Professor of St. Petersburg State Institute of Technology (Technical University) and a Head of Department of Optimization of Chemical and Biotechnological Equipment (since 2008), Head of the Lab of Process Intensification at Silicate Chemistry Institute of the Russian Academy of Science. Dr. Abiev has written more than 350 publications, 6 books, 5 chapters in a "New Handbook of chemist and technologist" (in Russian), 4 chapters in books (2 of them are issued in Germany and USA), more than 100 papers in peer-reviewed journals and more than 90 patents. His research interests are: Process Intensification, Microreactors, Process Simulation, Multiphase Flows, Heat and Mass Transfer intensification. He had received meny international research grants: 2014 (DAAD) at Institut für Mikroverfahrenstechnik (KIT), 2006 (DAAD) at TU Dresden, 1998 at Swiss Academy of Technical Science. He has been working as invited Professor in France – Ecole des Mines d'Ales (2016) and Laboratoire de Génie Chimique de Toulouse of INP de Toulouse (2017). Dr. Abiev is a member of Working Party on Mixing and a guest member of Working Party on Process Intensification, European Federation of Chemical Engineering.

Dr. Ritunesh Kumar is an Associate Professor in the Department of Mechanical Engineering, Indian Institute of Technology Indore. He received his PhD from Indian Institute of Technology, Delhi in the area of Refrigeration and Air-Conditioning. Prior to joining IIT Indore he had worked with Tata Consulting Engineers Limited, Vikhroli, Mumbai.
His research interest include heat transfer at micro-scale, desiccant cooling systemans and biofuels.

GIAN

Government of India
Ministry of Human Resource Development

Global Initiative on Academic Network

11th to 23rd December 2023

Two-Phase Flows In Micro And Milli Channels: Theoretical Background, Experimental And Numerical Proofs Of Hydrodynamics, Heat And Mass Transfer

Indian Institute of Technology Indore,
Dept. of Mechanical Engineering

GIAN-Global Initiative on Academic Network Course on

TWO-PHASE FLOWS IN MICRO AND MILLI CHANNELS: THEORETICAL BACKGROUND, EXPERIMENTAL AND NUMERICAL PROOFS OF HYDRODYNAMICS, HEAT AND MASS TRANSFER

11th to 23rd December 2023

Overview

Minimization of the costs with simultaneous increase of the raw materials and energy use efficiency is a challenge for the modern world. One of the most effective tools to solve this task is the use of Process intensification, first proposed by Ramshaw 1995 [1] and then extended by Stankiewicz and Moulijn 2000 [2]. It has been postulated by Górak and Stankiewicz 2011 [3]: "With a growing population and an increasing awareness of the world's unsustainable waste and use of energy and resources, the process industry must look towards making a structural change. To do so, Process Intensification (PI) will be essential. Process intensification is defined as a set of often radically innovative principles ("paradigm shifts") in process and equipment design. Such principles can yield significant benefits in terms of process and chain efficiency, capital and operating expenses, quality, waste, process safety and more."

Among other methods of process intensification micro scaled devices play growing role in the industry, energetics and transport [2]. In microstructured chemical devices due to their small lateral sizes the capillary and viscous forces dominate on the inertial and gravitational forces, thus determining the structure of the flows.

In the past two-three decades throughout the world micro and minireactors are actively investigated as a potential replacement of conventional devices. The use of micro and mini technologies can improve the quality of end products, reducing energy and resource consumption, increase the manufacturing mobility and the possibility of its rapid readjusting to produce other products. Micro- and minireactors can reduce the space occupied by the plant, making it safer and more environmental friendly.

Mini and micro pumps, mixers, heat exchangers, reactors, extractors and valves (Hessel et al. 2005 [4]; The Catalogue 2009 [5]) are already developed and produced in small series. Cross section dimension of such equipment is usually in the range between 10 µm and 3 mm. It was proposed to distinguish between micro and mini scale in some articles. Boundary between them is considered to be about 100 µm. Upper boundary of miniscale according to several authors is in the range between 1 mm and 5.4 mm. A physically based limit for miniscale size of the pipes could be attributed to the Bond number

$$Bo = \frac{\Delta \rho g D^2}{\sigma}, \qquad (1)$$

imposing the balance between gravitational and capillary forces, (in some papers Eötvös number is used instead) corresponding to the critical value of Bo = 4, from which the upper limit of minichannels diameter follows:

$$D_{crit} = 2\sqrt{\frac{\sigma}{\Delta\rho g}}. \tag{2}$$

Microreactors can be competitive for the conducting fast reactions, when mass transfer limits a reaction rate, as well as when heat transfer is a crucial factor, when it is necessary to remove quickly heat from the reactants (see also Chapter 7 of this review). It is possible due to unusually high values of heat and mass transfer in microreactors, which could be up to two orders of magnitude higher than in conventional types of reactors (Hessel et al. 2005 [4]). Another significant advantage of microreactors is a very narrow residence time distribution that can substantially reduce the formation of byproducts in the consecutive reactions (Hessel et al. 2005 [4]; Kreutzer et al. 2005 [6]). Microreactors are used for the reactions in mixtures of gases as well as in gas-liquid, liquid-liquid (Kreutzer et al. 2005 [6]; Hessel et al. 2005 [7]),

In terms of design microreactors can be divided into single- and multichannel ones. Most favorable regime for conducting gas-liquid catalytic reactions is a slug flow (Kreutzer et al. 2005 [6]; Bauer et al. 2006 [8]). Gas-liquid slug flow regime is a consecutive flow of gas bubbles separated one from the other by liquid slugs. The advantages of this regime are a good mixing inside the liquid slug due to the so-called Taylor vortices, as well as short diffusion path for gas molecules penetrating through the liquid film between the bubble and the wall of the catalyst (Kreutzer et al. 2005 [6]; Bauer et al. 2006 [8]; Onea et al. 2009 [9]).

The extraordinary heat and mass transfer capacity results from the high surface-to-volume ratios within these devices as well as from a microfluidic flow regime – Taylor flow. This regime is characterised by a flow of two immiscible fluids in separate compartments and offers large interfacial areas, short diffusion distances, internal circulation vortices, and nearly plug flow behaviour (Kreutzer et al. 2005 [6]; Kreutzer et al. 2001 [10]).

Another interesting application of Taylor Gas-Liquid (Vapor-Liquid) flows are closed loop pulsating heat pipes (CLPHP) (Khandekar et al. 2003 [11]; Mehta and Khandekar 2014 [12]; Das et al. 2010 [13]; Khandekar et al. 2009 [14]; Bhagat and Watt 2015 [15]). Interestingly that one of the two main types of flow is slug flow (the other is annular flow), containing liquid slug and gas-vapor bubbles.

Despite such a great interest in this subject, results published in the literature are disjointed, sometimes even contradictory. In this regard, there is a need in reliable experimental data for mathematical models verification, as well as a building of physically based relations for the mass transfer in case of slug flow.

The presented course represents a general view to the mathematical modeling of hydrodynamics, heat and mass transfer of Gas-Liquid (or Vapor-Liquid) and Liquid-Liquid Taylor flows in micro channels by means of theoretical approach using classical equations and modern formulae necessary to complete the model. The theoretical estimations is proven by own and available in the literature experimental and numerical data.

References

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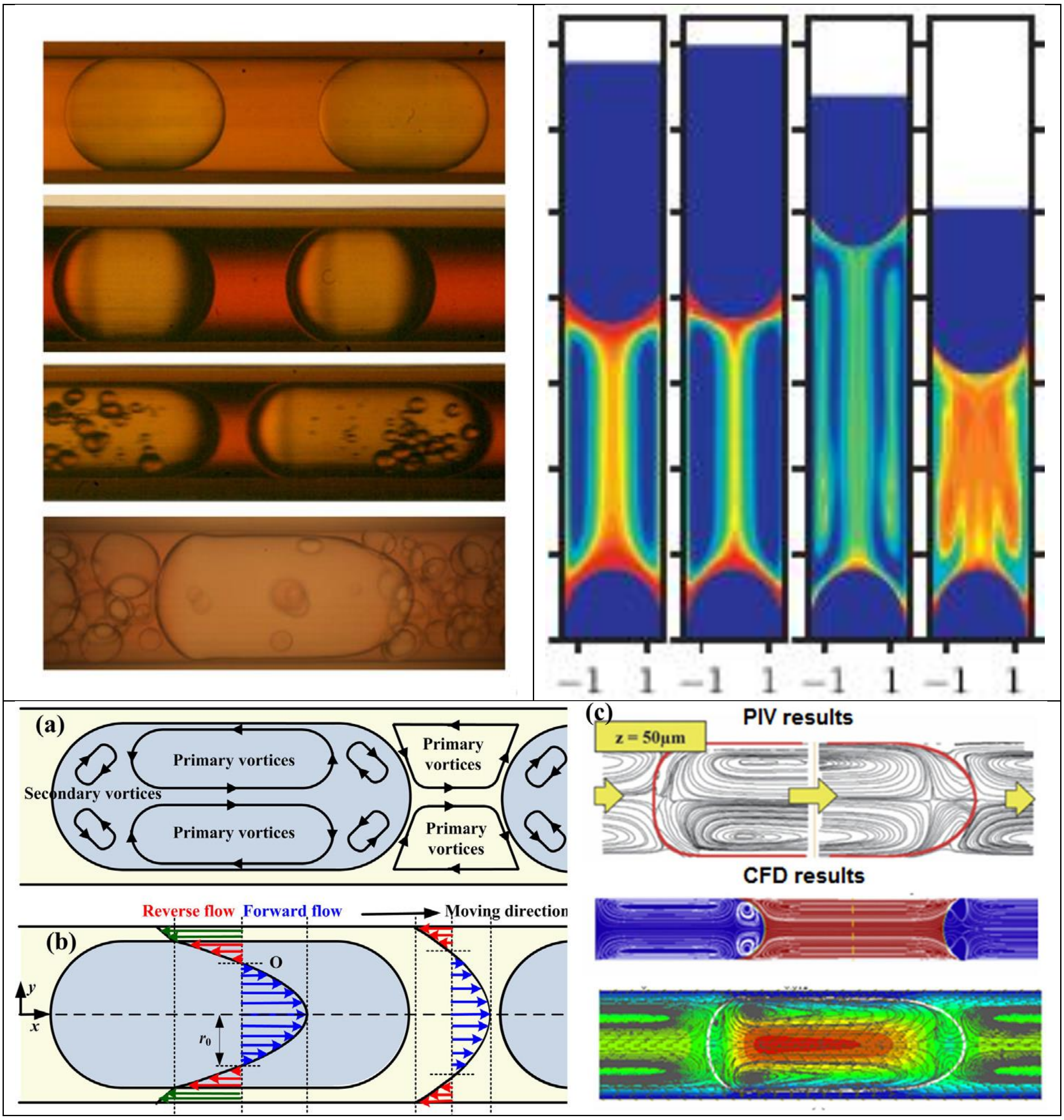
Objectives of the course:

- Exposing participants to the fundamentals of process intensification in general and by means of miniaturisation in particular: size effects by the transition from macro to milli and micro levels, dominating forces, general theoretical approaches for hydrodynamics, heat and mass transfer modelling.
- Building in confidence and capability amongst the participants in the application of two-phase micro reactors and extractors, two-phase micro mixers, two-phase micro heat exchangers, and their manufacturing techniques as well as the issues of

mathematical modelling and experimental technique of hydrodynamics, heat and mass transfer in two-phase micro flows, design and manufacturing of micro devices.

- Providing exposure to practical problems and their solutions, through case studies and live projects in two-phase micro reactors and extractors, two-phase micro mixers, two-phase micro heat exchangers,
- Enhancing the capability of the participants to identify, control and remove technical problems in micro heat exchangers like phases maldistribution, change in flow regime, the use of the enhanced method to generate two-phase flow, selection of optimal two-phase velocity for maximal performance, etc.



Details of the course:

Duration: December 11 – December 23, 2023 (12 days): 17 Lectures and 3 Tutorials + 3.5 hrs Exam

Tentative lectures Schedule

December 11 – Monday

Lecture 1 : 10:00 to 11:00 AM
Introduction: Fundamentals of process intensification.
Fundamentals of process intensification in general and by means of miniaturisation in particular. Size effects by the transition from macro to milli and micro levels, dominating forces, general theoretical approaches for hydrodynamics, heat and mass transfer modelling.

Lecture 2 : 11:15 to 12:15 AM
Fundamentals of microreactors design and fabrication.
Fundamentals of microreactors design and fabrication. Topologies of two-phase micro reactors and extractors, two-phase micro mixers, two-phase micro heat exchangers. Microfabrication in Metals, Ceramics and Polymers.

December 12 – Tuesday

Lecture 3 : 9:00 to 10:00 AM
Two phase flows in microreactors - 1.
Two phase flows in microreactors: Bubbly flow, Taylor flow, Annular flow, Churn flow, Transition flows. Experimental techniques to define flow regime.

Lecture 4 : 10:15 to 11:15 AM
Two phase flows in microreactors - 2.
Types of micro mixers used for Taylor flow. Coaxial-spherical micro mixer as a tool to better flow control.

December 13 – Wednesday

Lecture 5 : 09:00 to 10:00 AM
Fundamentals of Taylor flow hydrodynamics – 1
Theoretical approach to the Hydrodynamics of Taylor flow: continuity and Navier-Stokes equations. Aussilous-Quere and Han-Shikazono models for liquid film thickness.

Lecture 6 : 10:15 to 11:15 AM
Fundamentals of Taylor flow hydrodynamics – 2
Calculation procedure for two-phase Taylor flow: Bubble velocity, film thickness, slug velocity. Dimensionless criteria used for two-phase flows.

December 14 – Thursday

Lecture 7 : 09:00 to 10:00 AM
Fundamentals of Taylor flow hydrodynamics – 3
Calculation procedure for two-phase Taylor flow: Pressure gradients, velocity profiles. The shape of the elongated bubbles. Impact of flow direction on bubble velocity. Stagnation of bubbles.

Lecture 8 : 10:15 to 11:15 AM
Fundamentals of Taylor flow hydrodynamics – 4
Calculation procedure for two-phase Taylor flow: Circulation and by-pass flow modes for Taylor flow. Criterion of transition between two modes.

December 15 – Friday

Lecture 9 : 9:00 to 10:00 AM
Fundamentals of Taylor flow hydrodynamics – 5
Maldistribution problems and available solutions. Computer tomography results for maldistribution measurements.

Lecture 10: 10:15 to 11:15 AM
Fundamentals of Taylor flow hydrodynamics – 6
Calculation procedure for two-phase Taylor flow: Relation between dynamic and real gas hold-up ratio and bubble velocity. Pressure drop: several origins of energy losses. Impact of wettability of microchannels. Experimental and numerical corroboration of theoretical approach.

Lecture 11 : 11:30 to 12:30 AM
Fundamentals of heat transfer in two-phase flows in micro channels - 1.
Flows with and without phase change. Overview of state-of-the-art flow boiling and flow condensation calculations techniques.

December 16 – Saturday

Tutorial 1 : 9:00 to 10:00 AM
Problem solving session with examples: Calculation of two-phase Taylor flow hydrodynamics for gas-liquid flow in circular micro channels. Bubble velocity, film thickness, slug velocity, pressure drop, velocity profiles, shear stresses.
Tutorial - checking of results: 10:15 to 11:15 AM
Tutorial - discussion of results: 11:30 to 12:30 AM

December 17 – Monday

Lecture 12 : 10:15 to 11:15 AM
Fundamentals of heat transfer in two-phase flows in micro channels - 2.
Heat transfer in closed loop micro channel heat pipes (CLCHP). Oscillations in CLCHP. Comparison of oscillating and circulating modes in micro channel heat pipes.

Lecture 13 : 11:30 to 12:30 AM

Fundamentals of mass transfer in two-phase flows in micro channels - 1.

The paths of mass transfer for Gas-liquid and Liquid-Liquid flows. Bercic-Pintar and Kreutzer et. al. mass transfer models. Improved mass transfer models for Taylor flow in micro channels.

December 18 – Tuesday

Lecture 14 : 9:00 to 10:00 AM

Fundamentals of mass transfer in two-phase flows in micro channels - 2.

Experimental techniques for mass transfer measurements: PLIFI, chemical indicator methods. Applications of three-layer mathematical model to analyse experimental data.

Lecture 15 : 10:15 to 11:15 AM

Heat and mass transfer intensification in micro channels.

Heat and mass transfer intensification by means of Taylor flow: numerical and experimental results. Three-layer mathematical model of mass transfer of Taylor flow: geometry of Taylor vortices, application of three-layer to process optimisation.

December 19 – Wednesday

Lecture 16 : 9:00 to 10:00 AM

Conjugated hydrodynamics and mass transfer problem for two-phase flow in microchannels.

Use of three-layer mathematical model for mass transfer parameters calculation of two-phase Taylor flow in micro channels. Assessment of mass transfer coefficient. Frequency of circulations in two-phase flow.

Tutorial 2 : 10:15 to 11:15 AM

Problem solving session with examples: Calculations of three-layer mathematical model parameters of two-phase Taylor flow in micro channels.

December 20 – Thursday

Tutorial 3 : 11:30 to 12:30 AM

Problem solving session with examples: Comparison of three-layer mathematical model parameters with available experimental data.

Lecture 17 : 9:00 to 10:00 AM

Extension of hydrodynamics onto non-Newtonian fluids: velocity profiles in continuous and dispersed phases. Four combinations of Newtonian and non-Newtonian fluids.

December 21 – Friday

Lecture 18 : 10:15 to 11:15 AM

Three-layer model for non-Newtonian fluids: geometry of three-layer flow, velocity of circulations, bypass-to-circulation transition in microchannels, frequency of circulations.

December 22 – Saturday

9:00 to 12:30 AM
Course Evaluation (Exams for students)

Who can attend?

- Students (BTech/BSc/MSc/MTech/PhD) and Faculties from reputed academic institutions and technical institutions.
- Engineers and researchers from manufacturing, service and government organizations including R&D laboratories.

e-Certificate:

Participation certificate will be given to each participant.

Registration Fees:

UG students: Rs. 5000
PG and Research scholars: Rs. 8000
Faculty members: Rs. 10000
Industry/R&D Organizations: Rs. 15000
Foreigners: USD 500

How to register?

Step 1: Send an email to the course coordinator Dr. Ritunesh Kumar (ritunesh@iiti.ac.in) expressing your interest. After the confirmation email only, the payment should be done.

Step 2: The payment can be made through NEFT Transfer to the following account details: Name of the Beneficiary: Registrar, Indian Institute of Technology Indore; Name of Bank: Canara Bank; Branch Code: IIT Indore Campus; Branch Beneficiary Account No.: 1476101027440; Bank IFS Code: CNRB0006223. Payment can be made through demand draft also.

Course Instructor

Prof. Rufat Abiev
Department of Optimization of Chemical and Biotechnological Equipment
St. Petersburg State Institute of Technology, Russia

Brief Profile:

Prof. Rufat Abiev is one of University Professors of St. Petersburg State Institute of Technology (Technical University), he is a Head of Department of Optimization of Chemical and Biotechnological Equipment (since 2008).

In 2014 has received a research grant from German Academy Exchange Service (DAAD) for 1 month to perform investigations in Karlsruhe Institute of Technology (KIT), at Institut fuer Mikroverfahrenstechnik (Institute for Micro process engineering).

In 2006 Dr. Abiev has received a research grant from Altana-Quandt Foundation for 2 months and later in the same year a research grant from German Academy Exchange Service (DAAD) for 3 months. The research was made at the Technical University Dresden in the Department of Chemical Engineering. In 1998 he has received the grant of the Swiss Academy of engineering Science (SATW-Branco Weiss, Schweizerische Akademie der Technischen Wissenschaften). Since August, 1998 till March, 1999 worked as a trainee in laboratory of polymers branch of concern "CIBA Specialitaeten Chemie" in Basel (Switzerland).

In 2016 he has been invited as a Professor invitee in Ecole des Mines d'Ales (France) and in 2017 in Institute National Politechnique de Toulouse (Laboratoire de Genie Chimique, France) to perform joint research in the field of two-phase micro reactors.

Main directions of his scientific activity come down to work related to:

- process intensification in general, by use of external physical field and miniaturization in particular;
- hydrodynamics of two-phase flows in milli and micro channels, with the emphasis to the theoretical approach;
- modeling of Taylor two-phase flows;
- mass transfer in Taylor two-phase (gas-liquid and liquid-liquid) flows;
- heat transfer by boiling and condensation in the flow, non-isothermal vapor-liquid two-phase flows;
- intensification of mass heat exchange by forced convection, development of high performance micro heat exchangers and micro reactors;
- impinging-jets micro reactors for precipitation reactors;
- issues related to non-conventional devices and systems for energy conversion,
- micro channel heat pipes;
- the use of pulsations for various processes intensification.

Prof. Abiev has more than 450 publications (in general), including 5 books, 5 chapters in a "New Handbook of chemist and technologist" (in Russian), 2 chapters in “Engineering Ecology Handbook” (in Russian), and more than 90 refereed journal publications. Recently two book chapters are published by him in English: (1) “Direct

Numerical Simulations of Taylor bubbles in a square mini-channel: detailed shape and flow analysis with experimental validation" (H. Marschall, C. Falconi, C. Lehrenfeld, R. Abiev, M. Wörner, A. Reusken and D. Bothe. Springer-Verlag, The book 'Transport Processes at Fluidic Interfaces'; Buchreihe „Advances in Mathematical Fluid Mechanics", 2017, p. 663–679); (2) "Analysis of Hydrodynamics and Mass Transfer of Gas-Liquid and Liquid-Liquid Taylor Flows in Microchannels" (In the book: Santana, H. S., Lameu da Silva Jr, J., & Taranto, O. P. (2019). Process Analysis, Design, and Intensification in Microfluidics and Chemical Engineering (pp. 1-367). Hershey, PA: IGI Global, USA). He also has more than 90 issued or pending patents in Russia and Kazakhstan.

He has several research grants supported by Russian Foundation of Basic Research (one of them was performed in collaboration with Dr. Ritunesh Kumar group, IIT Indore), Russian Science Foundation, four from them are devoted to the process intensification in microfluidic devices (micro disperser, micro heat exchanger, micro reactor).

Prof. Abiev is a member of Editorial boards of two international journals: Theoretical Foundation of Chemical Engineering (Springer), Chemical Engineering Research and Design (Elsevier).

Prof. Abiev is a member of Working Party on Mixing and a guest member of Working Party on Process Intensification, European Federation of Chemical Engineering. In 2020 he was prize-winner of Russian Federation Government in the field of Education.

Course Coordinator

Dr. Ritunesh Kumar is an Associate Professor in the Department of Mechanical Engineering, Indian Institute of Technology Indore. He received his PhD from Indian Institute of Technology, Delhi in the area of Refrigeration and Air-Conditioning. Prior to joining IIT Indore he had worked with Tata Consulting Engineers Limited, Vikhroli, Mumbai.
His research interest include heat transfer at micro-scale, desiccant cooling systems and biofuels.

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