T.I.M.E. Projects/ Final Report

T.I.M.E. Distance learning postgraduate course: "particle-laden flows: theory and engineering applications"

Project leader: Politecnico di Milano – Dept. Civil and Environmental Engineering
Project coordinator: Gianandrea Vittorio Messa

Summary of the Project
The project consists in arranging a MOOC (Massive Online Open Course) on particle-laden flows, i.e. two-phase flows of a fluid and solid particles, which is built on a strong theoretical foundation but has a clear application-oriented view. The course consists of video lessons followed by a number of case studies. The video lessons are grouped into four modules, as follows: • Fundamentals of particle-laden flows. • Simulation of particle-laden flows. • Particle transport in slurry pipelines. • Solid particle erosion. The video lessons have been developed by Gianandrea Vittorio Messa (POLIMI) and Vaclav Matoušek (CVUT) and recorded at POLIMI with the support of METID. The case studies, in the form of text, images, tables, graphs etc., have been provided not only by the other project partners around their research expertise, but also by invited contributors from academia and industry. The course is now at the stage of debugging and testing by METID, and a first "beta" edition will be soon launched on the POLIMI-POK platform (expected Mar 2020). As a distinguished character of POLIMI-POK, the MOOC will be freely accessible and, therefore, it could be attended by students as well as academic and professional engineers. Additionally, upon approval by the competent authorities at POLIMI, the MOOC in beta version will be integrated in a PhD course offered to all PhD students at POLIMI (expected Apr-May 2020). In this course, co-taught by Gianandrea Vittorio Messa and Stefano Malavasi, the MOOC will be accompanied by frontal lessons and laboratory activities. Learning assessment will include the evaluation of a brief report in which the students analyze in detail a specific topic treated in the MOOC. All reports, reviewed and possibly improved by the teachers, might be provided as additional teaching material in the next edition of the MOOC. This, in addition to the ongoing collection of case studies, will make the MOOC self-sustaining and self-improving.
Results of the Project
Main results of the project have been the realization of the MOOC and its integration in a PhD course at POLIMI, already proposed to the Head of the Faculty Board of the Doctoral Program in Environmental and Infrastructure Engineering and currently under evaluation by the competent authorities. This required : • Preparing and shooting 19 video-lessons, including revision and debugging. • Developing all additional documentation required by POLIMI-METID («course details» page, outline forms, detailed program with learning objectives and quizes, student survey). • Preparing the case study form, sending the invitations to potential contributors, and collecting/reviewing the case studies received. At present, 9 case studies have been obtained, provided by Stefano Malavasi (project partner, POLIMI), José Gilberto Dalfré Filho (project partner, UNICAMP), Zhiguo Wang (project partner, Xi'an Shiyou University), Francisco Souza et al. (Federal University of Uberlândia, Brazil), François Avellan & Sebastián Leguizamón (EPFL-LMH, Switzerland), Magdalena Walczak & Javiera Aguirre (Pontificia

Universidad Católica de Chile), Giacomo Nutricato & Simone Gorini (ENI S.p.A., Italy), Harry Claydon & Mike Malin (CHAM – Concentration Heat and Momentum, UK), Thomas Senfter (MCI – The Entrepreneurial School, Austria).

- The preparation of a summary form proposal for the PhD course at POLIMI.

The detailed workflow after delivering the progress report on 15 Jun 2020 is as follows:

- 11 Jul 2019: Giacomo Nutricato & Simone Gorini (ENI S.p.A., Italy) provided their case study "GRE COMPOSITE MATERIAL FOR WELL COMPLETION SOLUTION"
- 22 Jul 2019: Gianandrea Vittorio Messa shot four video lessons.
- 12 Sep 2019: Gianandrea Vittorio Messa shot three video lessons.
- 24-27 Sep 2019: Gianandrea Vittorio Messa and Vaclav Matoušek attended the 19th International Conference on Transport and Sedimentation of Solid Particles in Cape Town, South Africa. They promoted of the project and had the first meeting with Thomas Senfter, who later contributed with his own case study.
- 09 Oct 2019: Harry Claydon & Mike Malin (Concentration Heat and Momentum, UK) provided their case study "CFD APPLICATION CASES INVOLVING PARTICLE-LADEN FLOWS".
- 10-11 Oct 2019: Vaclav Matoušek visited POLIMI and shot three lessons.
- 17 Oct 2019: Gianandrea Vittorio Messa presented the project at the TIME General Assembly in Centrale Supélec.
- 25 Oct 2019: Gianandrea Vittorio Messa shot three lessons.
- 08 Nov 2019: Gianandrea Vittorio Messa shot two lessons.
- 21 Nov 2019: Gianandrea Vittorio Messa shot two lessons, introductory lesson & trailer.
- Dec 2019-present: Gianandrea Vittorio Messa, Vaclav Matoušek, and METID have been involved in debugging and testing.
- 21 Jan 2020: Gianandrea Vittorio Messa submitted the MOOC outline forms (attached) to METID.
- 24 Jan 2020: Gianandrea Vittorio Messa and Vaclav Matoušek submitted the MOOC detailed programme (attached) to METID.
- 27 Jan 2020: Thomas Senfter (MCI – The Entrepreneurial School, Austria) provided his case study "HYDROCYCLONE OPTIMIZATION FOR THE REMOVAL OF IMPURITIES IN BIOWASTE CO-DIGESTION PROCESSES".
- 30 Jan 2020: Gianandrea Vittorio Messa and Stefano Malavasi submitted the summary form proposal for the PhD course at POLIMI (attached) to the Head of the Faculty Board of the Doctoral Program in Environmental and Infrastructure Engineering.
- 31 Jan 2020 : Gianandrea Vittorio Messa and METID handled the finalization of the student survey, obtained by customizing the forms developed by METID for the MOOCs on POLIMI-POK.

The METID staff required preparing, for each of the 19 lessons, a "storyboard" consisting in a power point presentation and a text document reporting the teacher's speech associated to each slide of the presentation (an example was attached to the progress report). Each storyboard was reviewed by METID, and, upon approval, used to develop the video lesson. Broadly speaking, preparing a storyboard required to more than one full-time working day, and the shooting of the corresponding video lesson about half of an hour, to which the video editing work done by METID shall be added.
The debugging required inspecting all provisional videos edited by METID and preparing, for each of them, a debug table (see attachment) listing all bugs, which mostly consisted in pronunciation errors, audio editing mistakes, or graphical/formatting mistakes in the background presentation. The debug table was then inspected by the METID, and the bugs fixed either by the teacher or by METID. In some cases, short audio clips were recorded. Broadly speaking, four debug tables could be produced in one full-time working day.

Target group/s and impact

The course was intended for Ph.D. students and professional engineers, but it might be also of interest to M.Sc. students. Even if the topics have been addressed from the fundamentals, the knowledge of material point mechanics, continuum mechanics, calculus, and basic fluid mechanics is strongly recommended. Many people could be potentially interested in the MOOC. On one side, particle-laden flows are encountered in many engineering fields. Given the research expertise of the proposers, the case studies presented in the course concerned mainly the mining and oil and gas sectors, with notes on hydraulic machinery and structures. However, similar phenomena are encountered in other sectors, including the food, the chemical, and the pharmaceutical industry. On the other side, particle-laden flow is such a special topic that it is unlikely to be the subject of courses offered by M.Sc. or PhD programs. Indeed, short courses and specialized workshops can be found, but their generally high fees prevent their attendance by students. Therefore, the MOOC might be of help to PhD students developing their thesis, as well as academic researchers and professional engineers interested in a first overview on the topic.

The first launch of the MOOC on the POLIMI-POK platform is expected around March 2020. Although the MOOC will be already accessible to everyone free of charge, the first edition might be intended as a “beta” one to be further improved. In fact, upon approval by the competent authorities of POLIMI, around April-May 2020 such “beta” edition of the MOOC will be integrated within a PhD course proposed by Gianandrea Vittorio Messa and Stefano Malavasi. If the PhD course is approved, it will be offered to all PhD students at POLIMI, who will provide a preliminary feedback on the MOOC and produce some teaching material that, under review and possible improvement by the teachers, might be provided as supplementary material in the next editions.

Since the very beginning of this project, effort has been constantly made by the team members to increase the visibility of the MOOC. The search for case studies provided by academic and industrial partners, often met at international conferences, should be interpreted in this light, in addition to the teachers’ willingness to establish new research collaborations with their peers. The promotion of the course and the collection of new case studies will continue after the end of the project. With the same goal in mind, after the launch of the first edition of the MOOC on POLIMI-POK, the upload of the same course on the LEARNIFY platform will be planned upon agreement among the parties (teachers of the MOOC, METID, TIME etc.). As mentioned in the initial project proposal, COURSERA might be also considered as an additional platform in the future.

Sustainability of the programme

Once the MOOC is available on the POLIMI-POK portal, even in the “beta” version, it might be virtually permanently provided without additional costs. However, the partners’ vision is of a project that will undergo further development after the end of the TIME funding. In particular, next planned actions are:

- Mar 2020. The “beta” version of the MOOC will be available online on the POLIMI-POK portal. Afterwards, the upload of the same course on the LEARNIFY platform will be planned upon agreement among the parties (teachers of the MOOC, METID, TIME etc.).
- Apr-May 2020. Upon approval by the competent authorities of POLIMI, the MOOC on POLIMI-POK will be used within the PhD course “PARTICLE-LADEN FLOWS: THEORY AND ENGINEERING APPLICATIONS”, taught by Gianandrea Vittorio Messa and Stefano Malavasi and opened to all PhD students at POLIMI. As part of the learning assessment, students will be asked to prepare a report in which a specific topic of the course is analyzed in detailed. After revision by the teachers and possible improvement, these reports might be provided as additional teaching material in the next edition of the course, launched in 2021.
- The search for additional case studies will continue, as well as the promotion of the MOOC. Opportunities might arise during conferences in which the partners of the project are

involved, such as the 21st Int. Conf. on Hydrotransport (May 2020, Edmonton, Canada), the 6th IAHR Europe Congress (Jun-Jul 2020, Warsaw, Poland), the 25th Int. Congress of Theoretical and Applied Mechanics (Aug 2020, Milano, Italy), and the 23rd Int. Conf. Wear of Materials (Apr 2021, Banff, Canada). All case studies will be included in the next edition of the course, launched in 2021.

- During 2020, it is planned to start arranging state-of-the-art review papers on the topics of the course, which will be published open access so that they might be provided as teaching material to the students of the MOOC. A state-of-the-art review paper on slurry pipe flow modelling and testing is currently at the stage of declaration of intents between Gianandrea Vittorio Messa and Vaclav Matoušek. Bringing the idea into practice will take about 1-2 years: the first step (identification of journal, search for co-authors, outline of paper structure etc.) might be undertaken during the 21st Int. Conf. on Hydrotransport in May 2020, of which both Gianandrea Vittorio Messa and Vaclav Matoušek are in the Technical Advisory Committee, or during the first week of June 2020, when Gianandrea Vittorio Messa is going to visit Vaclav Matoušek at CVUT. A second state-of-the-art review paper could concern slurry erosion, exploiting the experience of some of the team members on this topic. The role of José Gilberto Dalfré Filho as session co-chair at the 25th Int. Congress of Theoretical and Applied Mechanics and the recent enrolment of Gianandrea Vittorio Messa in the Steering Committee and the Editorial Team of the 23rd Int. Conf. Wear of Materials might create opportunities for the development of this second paper.

As a final note, it is observed that, in the context of a cooperation between POLIMI and XJTU, Stefano Malavasi and Gianandrea Vittorio Messa submitted to their Department an expression of interest to arrange visits to XJTU to establish new teaching and research collaborations. Particularly, they proposed a collaboration program concerning different topics, including particle-laden flows. Given that the MOOC project involved two partners from Xi'an (XJTU and Xi'an Shiyou University), the finalization of the collaboration program could occur in synergy with the MOOC, creating further opportunities to the partners.

Project expenses

The funding received from TIME (15 k€) have been mainly used for the arrangement of the video-lessons, to cover the expenses of mobility exchanges between the teachers, and to promote the visibility of the project. Detailed summary of the expenses is as follows:

- About 2500€ for the participation of Gianandrea Vittorio Messa at the 22nd Int. Conf. Wear of Materials (14-19 April 2019, Miami, USA).
- About 2500€ for the participation of Gianandrea Vittorio Messa at the 19th International Conference on Transport and Sedimentation of Solid Particles (24-27 September 2019, Cape Town, South Africa).
- About 500€ for the visit of Vaclav Matoušek to POLIMI (10-11 October 2019) to shoot three video lessons.
- About 500€ for the participation of Gianandrea Vittorio Messa to the TIME General Assembly in Centrale Supélec to present the project.
- 2000€ for the technical support of POLIMI-METID for the realization of the MOOC.

Next planned expenses are:

- About 2500€ for the participation of Gianandrea Vittorio Messa at the 21st Int. Conf. on Hydrotransport (6-8 May 2020, Edmonton, Canada).
- About 4500€ for covering the open-access fees of two state-of-the-art-review research, co-authored by the team members, which will be provided as an attachment to future editions

of the MOOC.

Members of the consortium

- Politecnico di Milano (IT-PoliMi, Project Leader)
- Ceské Vysoké Uceni Techniché v Praze (CZ-CVUT)
- Universidade Estadual de Campinas (BR-UNICAMP)
- Xi'an Jiaotong University (CN-XJTU)*

* Just before the submission of the project proposal, Dr. Zhiguo Wang left CN-XJTU and started working as Associated Professor at Xi'an Shiyou Univerisity, which is not a TIME member institution. Dr. Zhiguo Wang remained involved in the course and his earlier colleague from CN-XJTU, Professor Xu Donghai kindly accepted to be a reference contact for his university.

Key Staff (Name, Position, E-mail)

- Gianandrea Vittorio Messa, Assistant Professor at IT-POLIMI, main contact and course coordinator, gianandreavittorio.messa@polimi.it
- Václav Matoušek, Professor at CZ-CVUT, v.matousek@fsv.cvut.cz
- Stefano Malavasi, Professor at IT-POLIMI, stefano.malavasi@polimi.it
- José Gilberto Dalfré Filho, Assistant Professor at BR-UNICAMP, dalfre@fec.unicamp.br
- Zhiguo Wang, Associate Professor at Xi'an Shiyou Univerisity, wangzhiguo029@126.com
- Xu Donghai, Professor at CN-XJTU, xudonghai@mail.xjtu.edu.cn

Attachments

- ATTACHMENT 1: MOOC outline forms submitted to METID on 21 Jan 2020 by Gianandrea Vittorio Messa.
- ATTACHMENT 2: MOOC detailed programme submitted to METID on 24 Jan 2020 by Gianandrea Vittorio Messa and Vaclav Matoušek.
- ATTACHMENT 3: PhD course proposal submitted to the Head of the Faculty Board of the Doctoral Program in Environmental and Infrastructure Engineering on 30 Jan 2020 by Gianandrea Vittorio Messa and Stefano Malavasi.
- ATTACHMENT 4: Example of debug table.

POLITECNICO DI MILANO	Outline forms of MOOC-PLF **Author:** Gianandrea Vittorio Messa **Date:** 21/01/2020

OUTLINE MOOC "PARTICLE-LADEN FLOWS: THEORY AND ENGINEERING APPLICATIONS"

1 – EXTERNAL OUTLINE FORM

The external outline form includes the basic information that can be viewed also by the users not enrolled in the course.

NECESSARY INFORMATION

1. **MOOC title**
   PARTICLE-LADEN FLOWS: THEORY AND ENGINEERING APPLICATIONS

2. **MOOC subtitle**
   Solid particles carried along in a fluid flow: physical fundamentals, measurement techniques, and modelling frameworks in an application-oriented view.

3. **Description of the course:**
   The MOOC, developed in the context of a collaborative research project, will provide an application-oriented yet theoretically rigorous overview of particle-laden flows, i.e., two-phase flows of solid particles within a carrier fluid (liquid or gas). These flows are encountered in many engineering fields, including but not limited to the mining industry, the oil & gas industry, and the hydraulic engineering.

   Students attending this course will learn how particle-laden flows can be characterized from a physical and engineering point of view, and they will be able to decide the most appropriate approach for handling these flows at the design level, including different techniques for the numerical simulation as well as the physical testing in laboratory setups. After discussing these aspects in a general framework, special attention will be paid to two phenomena of considerable industrial impact, namely, the liquid-solid transport in pipelines and the damage produced by the travelling solids on pipeline components and hydraulic equipment.

   As an appendix to the course, a number of case studies will highlight the importance of particle-laden flows in academic research and engineering practice. As well as by the partners of the project, these case studies have been gratefully provided by **Francisco Souza** et al. (Federal University of Uberlândia, Brazil), **François Avellan** & **Sebastián Leguizamón** (EPFL-LMH, Switzerland), **Magdalena Walczak** & **Javiera Aguirre** (Pontificia Universidad Católica de Chile), **Giacomo Nutricato** & **Simone Gorini** (ENI S.p.A., Italy), **Harry Claydon** & **Mike Malin** (CHAM – Concentration Heat and Momentum, UK), **Thomas Senfter** (MCI – The Entrepreneurial School, Austria).

   You can access the course free of charge and completely online.

Con logo TIME: The MOOC project was financed within the "T.I.M.E. Call of Projects 2018-2019". Coordinator of the project is PoliMI - DICA (**Gianandrea Vittorio Messa**, contact person and course coordinator; and **Stefano Malavasi**), and the other partners are Czech Technical University in Prague (**Vaclav Matoušek**), University of Campinas (**José Gilberto Dalfré Filho**), Xi'an Jiaotong University (**Xu Donghai**), and Xi'an Shiyou University (**Zhiguo Wang**).

4. **Prerequisites**:
The MOOC was developed for M.Sc. undergraduates and post-graduate engineers. The following prerequisites are recommended: material point mechanics, continuum mechanics, calculus, and basic fluid mechanics.

5. **Teachers**:

Gianandrea Vittorio Messa

Course coordinator. Gianandrea Vittorio Messa was born in Monza (Milano, Italy) on 6th July 1984. He received the Master Degree cum laude in Civil Engineering and the PhD cum laude in Environmental and Infrastructure Engineering at Politecnico di Milano in 2009 and 2013, respectively. Since 2015, he is Assistant Professor at the Department of Civil and Environmental Engineering of the same university. He is member of the research group "Fluid Lab", led by Prof. Stefano Malavasi. His research interests mainly concern the numerical and physical modelling of particle-laden and related phenomena, such as hydrotransport processes and impact wear of materials. As a side activity, he also dealt with the topics of energy dissipation and cavitation in hydraulic devices.

Vaclav Matoušek

Václav Matoušek was born in Teplice, Czechoslovakia, in August 14, 1963. He received the Master Degree in Civil Engineering from the Czech Technical University (CTU) in Prague in 1986 and the PhD cum laude in Mechanical (Dredging) Engineering from the Delft University of Technology, the Netherlands, in 1997. From 2010, he is Full Professor of Water Engineering and Water Management at Faculty of Civil Engineering of CTU in Prague. Currently, he is Deputy Head of Dept. of Hydraulics and Hydrology at CTU and Senior Research Fellow with the Institute of Hydrodynamics, Academy of Sciences of Czech Republic. His research focuses primarily on two-phase flows with a special attention to pipeline transport of slurries, slurry pumping, rheology of mixtures, flow of rheologically active slurries, sediment transport in open channels and river morphology.

6. Estimated effort: about 5 hours per week to learn the basic concepts. However, in order to fully achieve the learning outcomes, at least further 10 hours per week of individual study is also recommended, yielding a total estimated effort of about 15 hours per week.

2 - INTERNAL OUTLINE FORM

The internal outline form can be accessed only by users enrolled in the course.

1. **Course description**

   The MOOC, developed in the context of a collaborative research project, will provide an application-oriented yet theoretically rigorous overview of particle-laden flows, i.e., two-phase flows of solid particles within a carrier fluid (liquid or gas). These flows are encountered in many engineering fields, including but not limited to the mining industry, the oil & gas industry, and the hydraulic engineering.

   Students attending this course will learn how particle-laden flows can be characterized from a physical and engineering point of view, and they will be able to decide the most appropriate approach for handling these flows at the design level, including different techniques for the numerical simulation as well as the physical testing in laboratory setups. After discussing these aspects in a general framework, special attention will be paid to two phenomena of considerable industrial impact, namely, the liquid-solid transport in pipelines and the damage produced by the travelling solids on pipeline components and hydraulic equipment.

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2. **Course information**

   The course is arranged into four weeks.

   The first week is dedicated to the **fundamentals of particle-laden flows**, including the key parameters and physical features of a two-phase solid-fluid system, the physical interactions between the solid particles and the turbulent fluid flow, and the Lagrangian particle equation of motion.

The second week is focused on the **simulation of particle-laden flows** based on Computational Fluid Dynamics techniques. Particular attention will be devoted to the frameworks for the description of the motion of the solid particles (Lagrangian / Eulerian) as well as to the methods to reproduce the effect of turbulence.

In the third week, the problem of **particle transport in slurry pipelines** will be addressed. The technical characterization of slurry pipeline flows will be followed by an in-depth analysis of the investigation methods at disposal of engineers and designers, namely, integral-scale models, experimental testing on both laboratory and field scales, and computational simulations.

The problem of **solid particle erosion**, that is, the material removal from pipeline components and hydraulic equipment caused by their interaction with the solid particles carried along with the flow, will be the topic of the fourth week. The phenomenon will be analyzed mostly from the fluid-dynamic perspective, and the common investigation methodologies will be presented assessing their pros, cons and current limitations.

Finally, a number of **application cases** provided by academic and industrial organizations allow gathering a more comprehensive view of significant issues related with particle-laden flows in science and engineering.

3. **Bibliography**:

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POLITECNICO DI MILANO	Detailed programme of MOOC-PLF **Author 1:** Gianandrea Vittorio Messa **Author 2:** Vaclav Matoušek **Date:** 24/01/2020

DETAILED PROGRAM OF MOOC "PARTICLE-LADEN FLOWS: THEORY AND ENGINEERING APPLICATIONS"

WEEK 1: FUNDAMENTALS OF PARTICLE-LADEN FLOWS

Contents

Multi-phase flows, two-phase flows, dispersed two-phase flows, particle-laden flows. The concepts of volume fraction and density of the mixture for mono-and poly-disperse particle-laden flows. Particle size distribution: sieve analysis, discrete and continuous number frequency distributions, cumulative number frequency distribution, log normal distribution. Practical condition for the validity of the monodisperse particles approximation. Characterization of particle shape: the particle spherical coefficient. The concept of maximum packing volume fraction. The concept of particle response time; derivation of the formula for the response time of a single-particle initially at rest in a uniform flow and its physical interpretation. The concept of particle Stokes number and its evaluation in turbulent flows. Distinction between disperse and dense particle-laden flows and classification of the coupling regimes. The Elgobashi's map of flow regimes. The concept of turbulence modulation. The particle equation of motion. Classification of the forces acting on a particle. Evaluation of the drag force acting on a single particle: the concept of unhindered fluid velocity. Assessment of the dependence of the drag coefficient upon the particle Reynolds number: the Schiller and Naumann formula for spherical particles and the Haider and Levenspiel formula for non-spherical ones. Other types of fluid-particle forces: buoyancy, pressure gradient force, virtual mass, history, shear lift, and rotational lift. Classification and modelling of particle-particle interactions. Modelling of particle-wall interactions: the correlation by Forder, Thew and Harrison.

Brief learning objectives

- **Classify** multi- and two-phase flows.
- **Recall** and **apply** the concepts of volume fraction and density of mixture.
- **Understand** and **explain** how the dispersed phase in a particle-laden flow can be characterized.
- **Discuss** the physical interactions between solid particles and a turbulent fluid flow.
- **Recognize** and **illustrate** the Lagrangian particle equation of motion
- **Evaluate** the importance of the different terms in the particle equation of motion for a given problem

Detailed learning objectives

- **1_1_01 – Classify** multi- and two-phase flows.
- **1_1_01 – Recall** and **apply** the concepts of volume fraction and density of mixture.
- **1_1_01 – Illustrate** and **manage** their extension to polydisperse mixtures.
- **1_1_02 – Understand** the key components of a sieve analysis.
- **1_1_02 – Manage** the concepts of particle size distribution.
- **1_1_02 – Evaluate** whether a mixture of particles can be modeled as monodisperse.
- **1_1_02 – Explain** how particle shape can be characterized.
- **1_1_02 – Define** the concept of packing volume fraction.

- **1_1_03 – Define** the particle response time and the particle Stokes number.
- **1_1_03 – Derive** the expression of particle response time for 1D Stokes flow.
- **1_1_03 – Explain** the concept of particle Stokes number in turbulent flow.
- **1_1_03 – Discuss** its implications on particle motion.
- **1_1_04 – List** and **describe** the coupling regimes.
- **1_1_04 – Illustrate** and **apply** the Elgobashi's map.
- **1_1_04 – Explain** the concept of turbulence modulation.
- **1_1_05 – Classify** the type of forces acting on a particle in a particle-laden flow.
- **1_1_05 – Define** the drag force and **characterize** the drag coefficient.
- **1_1_05 – Explain** the concept of unhindered fluid velocity.
- **1_1_05 – Discuss** the effect of particle shape on the drag coefficient.
- **1_1_05 – List** the different types of fluid-particle forces.
- **1_1_05 – Outline** the models for particle-particle and particle-wall collisions.

Questions

- Consider a mixture of glass beads with density 2500 kg/m^3 in oil with density 830 kg/m^3. If the density of the mixture is 1080.5 kg/m^3, what is the volume fraction of the glass beads? [Answer: 0.15]

- The particle spherical coefficient:
  - ☐ is the ratio between the actual surface area of the particle and the surface area of a sphere having the same volume.
  - ☒ is always smaller than or equal to one.
  - ☒ is higher for glass beads than for natural sands.
  - ☐ does not affect the flow resistance encountered by a particle travelling in a fluid.

- Consider a spherical particle, initially at rest in a uniform flow. Assume that: (i) the motion of the particle is mainly driven by drag force and particle inertia; (ii) the particle is sufficiently small so that the Stokes flow approximation holds. If the particle reaches 86.4% of the uniform flow velocity after 1 s, what is the particle response time? [Answer: 0.5 s]

- Compared to fine particles, coarse particles
  - ☒ are likely to increase the level of turbulence of the carrier fluid.
  - ☐ are likely to have smaller particle response time.
  - ☒ require lower relative velocity for the Stokes flow approximation to hold.
  - ☐ in Stokes flow, are likely to experience lower drag force if the relative velocity is the same.

- According to the particle-wall collision model by Forder, Thew and Harrison
  - ☐ the restitution coefficients are a function of the particle incident velocity
  - ☐ the normal restitution coefficient is higher than the tangential restitution coefficient
  - ☐ the normal restitution coefficient is maximum for normal impingement
  - ☒ in the case of normal impingement, the particle rebounding velocity is less than half of the incident velocity.

WEEK 2: SIMULATION OF PARTICLE-LADEN FLOWS

Contents

Experimental testing and numerical modelling as problem-solving approaches in engineering fluid mechanics, with focus on particle-laden flows. Eulerian-Lagrangian models and Eulerian-Eulerian models: basic idea and main challenges. Classification of particle-laden flow models according to the way in which turbulence is treated: DNS-based, LES-based, and RANS-based models. Implications of resolving all scales of turbulence in DNS-based models. Notes on the Navier-Stokes equations for single-phase flows. Fully resolved DNS-based Eulerian-Lagrangian models: basic idea, applicability constraints, and solution procedure. Point-particle DNS-based Eulerian-Lagrangian models: basic idea, applicability constraints, evaluation of the fluid-particle forces, and solution procedure. Notes on the RANS-based turbulence modelling in single-phase flows: the Reynolds averaging and the Reynolds decomposition, the RANS equations and their extension to unsteady flows (U-RANS). RANS-based Eulerian-Lagrangian models with point-particle approximation: applicability constraints and evaluation of the fluid-particle forces. The parcel approach. Eulerian-Eulerian models: origin of the conservation equations, types of coupling, interfacial momentum transfer term, and constitutive equations. Modelling of turbulent flows using the Eulerian-Eulerian approach. Challenges in solving the instantaneous conservation equations. The double-average approach and the consequences of the choice of the second averaging operator: origin of the phase diffusion fluxes and of the turbulent dispersion force.

Brief learning objectives

- **List** and **classify** the different modelling approaches**.**
- **Understand** and **explain** the theoretical basis of each modelling approach.
- **Recognize** the basic equations of each modelling approach.
- **Discuss** pros and cons of each approach in a general fashion.
- **Recommend** the best modelling approach for a specific problem

Detailed learning objectives

- **2_0_01 – List** the main investigation approaches in fluid mechanics and **explain** their pros and cons.
- **2_0_01 – Illustrate** the concept of synergistic problem solving.
- **2_0_01 – Highlight** the greater challenges faced when dealing with particle-laden flows.
- **2_0_01 – Explain** the basic idea and **discuss** pros and cons of Eulerian-Eulerian and Eulerian-Lagrangian modelling.
- **2_0_01 – Propose** the best modelling approach for a given problem.
- **2_0_01 – Discuss** Eulerian-Eulerian and Eulerian-Lagrangian modelling in the light of the coupling regime.
- **2_0_01 – Classify** the modelling approaches in relation with the treatment of turbulence.
- **2_1_01 – Discuss** the implications of resolving all turbulence scales.
- **2_1_01 – Master** the Navier-Stokes equations for single-phase flow.
- **2_1_01 – Explain** the basic idea of fully resolved and point-particle DNS-based Eulerian-Lagrangian models and **discuss** the implications on particle size.
- **2_1_02 – Understand** the concept of Reynolds-averaging and **master** the RANS/U-RANS for single-phase flow.
- **2_1_02 – Explain** the basic idea of point-particle RANS-based Eulerian-Lagrangian models.
- **2_1_02 – Illustrate** the parcel approach.

- **2_1_02 – Explain** how the drag force is modeled in RANS-based Eulerian-Lagrangian models with point-particle approximation.
- **2_2_01 – Outline** the nature of the conservation equations in the Eulerian-Eulerian models.
- **2_2_01 – List** the different types of coupling in the Eulerian-Eulerian models.
- **2_2_01 – Characterize** the interfacial momentum transfer term in Eulerian-Eulerian models.
- **2_2_01 – Recognize** and **classify** the constitutive equations of Eulerian-Eulerian models.
- **2_2_02 – Discuss** the implications of resolving the instantaneous Eulerian-Eulerian equations for turbulent flows.
- **2_2_02 – Explain** the basic idea of the double-average approach.
- **2_2_02 – Assess** the implications of the choice of the second average operator.
- **2_2_02 – Describe** the origin of phase diffusion fluxes and turbulent dispersion force.
- **2_2_02 – Identify** the main challenges of Eulerian-Eulerian modelling of turbulent particle-laden flows.

Questions

- When modelling four-way coupled particle-laden flows with the Eulerian-Lagrangian approach, one:
  - ☒ might use the soft-sphere model to account for particle-particle interactions.
  - ☐ might include phase diffusion fluxes in the mass conservation equation of the solid phase.
  - ☐ might expect the computational burden to be lower than if using a two-fluid model.
  - ☐ might ignore the effect of the fluid on the particles.

- The computational cost of Eulerian-Eulerian models increases with the amount of solids in the flow:
  - ☐ True
  - ☒ False

- Phase diffusion fluxes
  - ☒ are related with the modelling of turbulence in the Eulerian-Eulerian framework.
  - ☒ appear also in the momentum conservation equations of the fluid phase.
  - ☐ appear when the Favre averaging is used in the double-average approach.
  - ☒ account for the turbulent dispersion of particles.

- Broadly speaking, the size of the computational cells
  - ☒ is smaller when using DNS-based models than when using RANS-based models.
  - ☐ is not related with the size of the particles.
  - ☒ in DNS-based models, decreases when the Reynolds number increases.
  - ☐ in RANS-based models, is affected by the characteristic size of the smallest eddies.

- In Eulerian-Eulerian models one cannot see the individual particles
  - ☒ True
  - ☐ False

WEEK 3: PARTICLE TRANSPORT IN SLURRY PIPELINES

Contents

Definition of slurry and application fields of slurry pipes. Production in slurry pipe transport: flow rate related parameters. Efficiency in slurry pipe transport: Specific Energy Consumption, hydraulic gradient and pipe characteristic curve. Safety in slurry pipe transport: deposition-limit velocity. Flow regimes of slurry transport in horizontal pipes: pseudo-homogeneous flow, heterogeneous flow, partially- and fully-stratified flow. Complex slurry flows of fine and course solids in a carrier liquid. Major predicted quantities for transport system design and operation and modelling approaches for slurry pipe flows. Relative Solids Effect. Dominant friction mechanisms in the different slurry flow regimes. The equivalent liquid model for pseudo-homogeneous flow. Layered models for partially- and fully-stratified flows. The multi-component model for settling slurries of any grading profile. Laboratory versus field testing: typical measured quantities in slurry testing. Continuous in-line monitoring of slurry discharge: magnetic flow meters and Coriolis mass flow meters. Laboratory pressure measurements using differential pressure transmitters. Continuous in-line monitoring of slurry density and delivered concentration. Experimental characterization of the distribution of solids over the pipe section: γ-ray radiometric devices and Electric Resistance Tomography. Computational Fluid Dynamics of slurry pipe flows: opportunities and challenges of Eulerian-Lagrangian and Eulerian-Eulerian models. The β-σ two-fluid model for fully suspended slurry flows.

Brief learning objectives

- **Recognize** the engineering relevance of slurry pipe transport.
- **Recall** and **explain** the technical parameters of most engineering interest.
- **Analyze** the common approaches for the engineering design and management of slurry pipelines.
- **Understand** and **discuss** their strengths and limitations.

Learning objectives

- **3_1_01 – Define** what a slurry is.
- **3_1_01 – Know** and **use** the formulas for the flow rate of mixture and average velocity of slurry flow.
- **3_1_01 – Define** the Specific Energy Consumption (SEC).
- **3_1_01 – List** the main parameters affecting the friction losses.
- **3_1_01 – Define** and **discuss** the pipe characteristic curve.
- **3_1_01 – Define** the deposition limit velocity and **list** the parameters affecting this variable.
- **3_1_01 – Define** in-situ and delivered concentrations, and **explain** the difference between the two.
- **3_1_01 – Classify** and **discuss** the different flow regimes of slurry flow in horizontal pipes.
- **3_1_02 – List** the modeling approaches for slurry pipe flows.
- **3_1_02 – List** the major predicted quantities.
- **3_1_02 – Illustrate** the concept of Relative Solids Effect (RSE) for the evaluation of the frictional losses.
- **3_1_02 – Draw** the typical characteristic curve of pseudo-homogeneous flow, heterogeneous flow, partially stratified and fully stratified flow and **identify** the physical mechanisms contributing to the frictional losses.
- **3_1_02 – Explain** the basic idea of the equivalent liquid model.
- **3_1_02 – Identify** the parameters affecting the frictional losses in heterogeneous flow.
- **3_1_02 – Explain** the basic idea of layered models.
- **3_1_02 – Recognize** the challenges related with polydisperse slurries.

- **3_1_03 – Illustrate** pros and cons of laboratory and field testing of slurry pipe flows.
- **3_1_03 – List** the key measurements in slurry pipe flows.
- **3_1_03 – Mention** and **discuss** commonly used instruments to measure the slurry discharge, the solids concentration, and the local distribution of solids within the pipe.
- **3_1_04 – Discuss** strengths and limitations of Computational Fluid Dynamics as a tool for handling slurry pipe flows. Refine the evaluation referring to the specific modelling approaches (Eulerian-Eulerian vs Eulerian-Lagrangian).
- **3_1_04 – Identify** the main flow parameters that Eulerian-Eulerian models can provide.
- **3_1_04 – Explain** the main features of the β-σ model.

Questions

- A sand-water slurry with specific gravity 2.6 flows in a horizontal pipe at mixture flow rate of 0.100 m^3/s. If the volumetric flow rate of the carrier liquid is 0.075 m^3/s and the hydraulic gradient is 0.20 m/m, what is the Specific Energy Consumption in dimensionless unit and in kWh/(ton-km)? [Answer: 0.308 [-], which is 0.84 kWh/(ton-km)]

- The pipe characteristic curve of slurry flow in a horizontal pipe:
  - ☐ is monotonically increasing for partially- and fully-stratified slurries.
  - ☒ accounts for the effect of the particles on the frictional losses.
  - ☐ is not dependent upon the delivered concentration.
  - ☐ has the Specific Energy Consumption on the vertical axis.

- The main friction mechanism in pseudo-homogenous flow is the direct contact between the particles and the pipe wall.
  - ☐ True
  - ☒ False

- The inverted U-loop is widely used to determine
  - ☐ The in-situ solid concentration.
  - ☒ The delivered solid concentration.
  - ☐ The slurry temperature.
  - ☐ The concentration distribution over the pipe section.

- The β-σ two-fluid model
  - ☐ is based on the Eulerian-Lagrangian approach.
  - ☐ is able to predict the formation of a stationary bed of particles.
  - ☒ includes phase diffusion fluxes in all conservation equations.
  - ☒ gives its name to the two main calibration parameters.

WEEK 4: SOLID PARTICLE EROSION

Contents

Definition of solid particle erosion and notes on the different types of erosion. Cross subject nature of the topic of impact erosion. Notes on the main erosion mechanisms of materials with brittle and ductile behaviors. Analysis of the parameters affecting the impact erosion characteristics: target-related parameters (mechanical behavior, density, and Vickers hardness), particle-related parameters (size, shape, and particle material), fluid-dynamic parameters (impact velocity and impact angle). Effect of solid loading: the screening effect. Effect of time: feasibility of the steady-state erosion approximation. The direct impact test: basic idea, control variables, and output variables. The Integral Erosion Ratio. Comparative analysis of dry and wet direct impact tests considering the fluid dynamic characteristics of the particle-laden flow, the experimental setups, and the testing procedure. Spurious effect of particle degradation in wet direct impact tests. The standard methodology for predicting the impact erosion based on Computational Fluid Dynamics: calculation procedure, main assumptions, and their consequences. Origin and application of erosion models. The erosion model by Oka and co-workers. Notes on the sources of uncertainty of the erosion predictions. Detailed analysis of the main flaws of the standard methodology for CFD-based erosion prediction (dilute flow, steady-state assumption, point-particle approximation, uncertain applicability of erosion models) and recent attempts to overcome them.

Brief learning objectives

- **Recognize** the engineering relevance of solid particle erosion.
- **Identify** the key parameters affecting solid particle erosion and **explain** their role.
- **Describe** the different investigation methods and **discuss** their strengths and limitations.
- **Recognize** the currently open issues in solid particle erosion modelling.

Detailed learning objectives

- **4_1_01 – Classify** the different types of erosion.
- **4_1_01 – Explain** the effect of particle impact angle on the impact erosion of brittle and ductile targets.
- **4_1_01 – Identify** the material- and particle-related parameters affecting impact erosion.
- **4_1_01 – Identify** the particle-related parameters affecting impact erosion.
- **4_1_01 – Describe** direct and indirect effects of particle size and shape on impact erosion.
- **4_1_01 – Discuss** the effect of impact velocity on impact erosion.
- **4_1_01 – Illustrate** the effect of solid loading and **explain** the screening effect.
- **4_1_01 – Illustrate** the effect of time and **discuss** the feasibility of steady-state erosion approximation.
- **4_1_02 – Describe** the direct impact test.
- **4_1_02 – Identify** the control and output variables in a direct impact test.
- **4_1_02 – Characterize** dry and wet direct impact tests from the fluid dynamic point of view.
- **4_1_02 – Justify** the different erosion behaviors observed in dry and wet direct impact tests.
- **4_1_02 – Derive** the expression for the Integral Erosion Ratio in dry and wet direct impact tests.
- **4_1_03 – Illustrate** the standard methodology for CFD-based erosion prediction.
- **4_1_03 – List** its main assumptions of this methodology.
- **4_1_03 – List** the main output erosion-related variables and **explain** how they are obtained.
- **4_1_03 – Define** what an erosion models is.
- **4_1_03 – Classify** erosion models based on their origin.
- **4_1_03 – Explain** how empirical erosion models can be obtained from a dry direct impact test.
- **4_1_03 – Cite** a widely used erosion model.

- **4_1_04 – List** the main limitations of the standard methodology for CFD-based erosion prediction.
- **4_1_04 – Explain** the quasi-static approach to model unsteady-state erosion.
- **4_1_04 – Illustrate** the motivation behind the mixed Eulerian-Eulerian / Eulerian-Lagrangian approach.
- **4_1_04 – Understand** the critical issues related with point-particle approximation and **mention a** possible strategy to overcome them.
- **4_1_04 – Mention** possible strategies to overcome the inaccuracies inherent in the use of empirical erosion models taken from the literature.

Questions

- In a wet direct impact test, the sample reduces its mass by 0.8 g in 30 minutes. Knowing that the jet bulk-mean velocity is 30 m/s, the nozzle diameter is 8 mm, the delivered concentration is 1%, and the particle density is 2650 kg/m^3, determine the Integral Erosion Ratio [Answer = 1.39E-5 kg/kg].

- The erosion produced by an air-solid jet hitting a sample with ductile behavior.
  - ☐ is maximum when the jet is perpendicular to the sample surface.
  - ☒ increases with the jet velocity.
  - ☐ linearly increases with the solid loading.
  - ☒ is affected by the shape of the particles.

- In the standard methodology for erosion prediction
  - ☒ the computational burden is strongly affected by the solid loading.
  - ☒ the particles are interpreted as point sources of momentum.
  - ☐ use is typically made of empirical erosion models obtained from wet direct impact tests.
  - ☐ the particle-laden flow is calculated using a two-fluid model.

- Compared to those obtained in dry direct impact tests, the results of wet direct impact test might suffer inaccuracies due to the spurious effect of particle rounding and fragmentation because:
  - ☒ The setups for wet direct impact tests usually involve a recycled use of the particles.
  - ☐ The impact velocities are higher in wet direct impact tests.
  - ☐ The actions exerted by a liquid on the particles are stronger that those exerted by a gas.
  - ☐ Inter-particle collisions are more likely to occur in wet direct impact tests.

- The quasi-static modelling of erosion:
  - ☐ is expected to improve the accuracy of the predictions mainly at low testing times.
  - ☐ was specifically developed to capture the screening effect.
  - ☒ typically uses moving mesh algorithms.
  - ☒ is likely to increase the calculation time compared to the standard methodology.

ATTACHMENT 3: PhD course proposal submitted to the Head of the Faculty Board of theDoctoral Program in Environmental and Infrastructure Engineering on 30 Jan 2020 by Gianandrea Vittorio Messa and Stefano Malavasi. Currently under evaluation by the competent authorities at POLIMI.

Summary Form

Year	2019/2020		
Assignment type	Doctoral		
Course	PARTICLE-LADEN FLOWS: THEORY AND ENGINEERING APPLICATIONS.		
Professor	Gianandrea Vittorio Messa Stefano Malavasi		
Cfu	5.00 The course includes 1.5 credits in Innovative Teaching as follows: • MOOC	Course type	Mono-disciplinary

PhD Course	From (inclusive)	To (exclusive)	Title of the Course
MI (1378) - INGEGNERIA AMBIENTALE E DELLE INFRASTRUTTURE / ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING	A	ZZZZ	PARTICLE-LADEN FLOWS: THEORY AND ENGINEERING APPLICATIONS.

Detailed Programme and foreseen learning results:

The course will be divided into two parts, broadly corresponding to 2.5 CFU each.

The first part will be given partly in the form of a MOOC, developed by the teachers and available on the POLIMI-POK platform, and partly in the form of frontal lessons. The MOOC consists of 19 video-lessons organized into four weeks, followed by case studies provided by academic and industrial contributors. For each of the four weeks of the MOOC: (i) the teachers will introduce the topics of the week through a frontal lesson; (ii) the students will attend the video lessons of the week and complement them with their own individual study; (ii) class activities including further deepening of the topics of the video lessons, document analysis, debate, project-based learning will be managed by the teachers.

Detailed program and learning outcomes of the four weeks are as follows.

WEEK 1: FUNDAMENTALS OF PARTICLE-LADEN FLOWS
(teacher: Gianandrea Vittorio Messa, Politecnico di Milano)
Contents
Multi-phase flows, two-phase flows, dispersed two-phase flows, particle-laden flows. The concepts of volume fraction and density of the mixture for mono-and poly-disperse particle-laden flows. Particle size distribution: sieve analysis, discrete and continuous number frequency distributions, cumulative number frequency distribution, log normal distribution. Practical condition for the validity of the monodisperse particles approximation. Characterization of particle shape: the particle spherical coefficient. The concept of maximum packing volume fraction. The concept of particle response time; derivation of the formula for the response time of a single particle initially

at rest in a uniform flow and its physical interpretation. The concept of particle Stokes number and its evaluation in turbulent flows. Distinction between disperse and dense particle-laden flows and classification of the coupling regimes. The Elgobashi's map of flow regimes. The concept of turbulence modulation. The particle equation of motion. Classification of the forces acting on a particle. Evaluation of the drag force acting on a single particle: the concept of unhindered fluid velocity. Assessment of the dependence of the drag coefficient upon the particle Reynolds number: the Schiller and Naumann formula for spherical particles and the Haider and Levenspiel formula for non-spherical ones. Other types of fluid-particle forces: buoyancy, pressure gradient force, virtual mass, history, shear lift, and rotational lift. Classification and modelling of particle-particle interactions. Modelling of particle-wall interactions: the correlation by Forder, Thew and Harrison.

Foreseen learning outcomes
At the end of week 1, students will be able to:

- Classify multi- and two-phase flows.
- Recall and apply the concepts of volume fraction and density of mixture.
- Understand and explain how the dispersed phase in a particle-laden flow can be characterized.
- Discuss the physical interactions between solid particles and a turbulent fluid flow.
- Recognize and illustrate the Lagrangian particle equation of motion.
- Evaluate the importance of the different terms in the particle equation of motion for a given problem.

WEEK 2: SIMULATION OF PARTICLE-LADEN FLOWS
(teacher: Gianandrea Vittorio Messa, Politecnico di Milano)

Contents
Experimental testing and numerical modelling as problem-solving approaches in engineering fluid mechanics, with focus on particle-laden flows. Eulerian-Lagrangian models and Eulerian-Eulerian models: basic idea and main challenges. Classification of particle-laden flow models according to the way in which turbulence is treated: DNS-based, LES-based, and RANS-based models. Implications of resolving all scales of turbulence in DNS-based models. Notes on the Navier-Stokes equations for single-phase flows. Fully resolved DNS-based Eulerian-Lagrangian models: basic idea, applicability constraints, and solution procedure. Point-particle DNS-based Eulerian-Lagrangian models: basic idea, applicability constraints, evaluation of the fluid-particle forces, and solution procedure. Notes on the RANS-based turbulence modelling in single-phase flows: the Reynolds averaging and the Reynolds decomposition, the RANS equations and their extension to unsteady flows (U-RANS). RANS-based Eulerian-Lagrangian models with point-particle approximation: applicability constraints and evaluation of the fluid-particle forces. The" parcel approach. Eulerian-Eulerian models: origin of the conservation equations, types of coupling, interfacial momentum transfer term, and constitutive equations. Modelling of turbulent flows using the Eulerian-Eulerian approach. Challenges in solving the instantaneous conservation equations. The double-average approach and the consequences of the choice of the second averaging operator: origin of the phase diffusion fluxes and of the turbulent dispersion force.

Foreseen learning outcomes
At the end of week 2, students will be able to:

- List and classify the different modelling approaches.

- Understand and explain the theoretical basis of each modelling approach.
- Recognize the basic equations of each modelling approach.
- Discuss strengths and limitations of each approach in a general fashion.
- Recommend the best modelling approach for a specific problem

WEEK 3: PARTICLE TRANSPORT IN SLURRY PIPELINES
(teachers: Vaclav Matoušek, Czech Technical University in Prague; Gianandrea Vittorio Messa, Politecnico di Milano)

Contents
Definition of slurry and application fields of slurry pipes. Production in slurry pipe transport: flow rate related parameters. Efficiency in slurry pipe transport: Specific Energy Consumption, hydraulic gradient and pipe characteristic curve. Safety in slurry pipe transport: deposition-limit velocity. Flow regimes of slurry transport in horizontal pipes: pseudo-homogeneous flow, heterogeneous flow, partially- and fully-stratified flow. Complex slurry flows of fine and course solids in a carrier liquid. Major predicted quantities for transport system design and operation and modelling approaches for slurry pipe flows. Relative Solids Effect. Dominant friction mechanisms in the different slurry flow regimes. The equivalent liquid model for pseudo-homogeneous flow. Layered models for partially- and fully-stratified flows. The multi-component model for settling slurries of any grading profile. Laboratory versus field testing: typical measured quantities in slurry testing. Continuous in-line monitoring of slurry discharge: magnetic flow meters and Coriolis mass flow meters. Laboratory pressure measurements using differential pressure transmitters. Continuous in-line monitoring of slurry density and delivered concentration. Experimental characterization of the distribution of solids over the pipe section: γ-ray radiometric devices and Electric Resistance Tomography. Computational Fluid Dynamics of slurry pipe flows: opportunities and challenges of Eulerian-Lagrangian and Eulerian-Eulerian models. The β-σ two-fluid model for fully suspended slurry flows.

Foreseen learning outcomes
At the end of week 3, students will be able to:
- Recognize the engineering relevance of slurry pipe transport.
- Recall and explain the technical parameters of most engineering interest.
- Analyze the common approaches for the engineering design and management of slurry pipelines.
- Understand and discuss their strengths and limitations.

WEEK 4: SOLID PARTICLE EROSION
(teacher: Gianandrea Vittorio Messa, Politecnico di Milano)

Contents
Definition of solid particle erosion and notes on the different types of erosion. Cross subject nature of the topic of impact erosion. Notes on the main erosion mechanisms of materials with brittle and ductile behaviors. Analysis of the parameters affecting the impact erosion characteristics: target-related parameters (mechanical behavior, density, and Vickers hardness), particle-related parameters (size, shape, and particle material), fluid-dynamic parameters (impact velocity and impact angle). Effect of solid loading: the screening effect. Effect of time: feasibility of the steady-state erosion approximation. The direct impact test: basic idea, control variables, and

output variables. The Integral Erosion Ratio. Comparative analysis of dry and wet direct impact tests considering the fluid dynamic characteristics of the particle-laden flow, the experimental setups, and the testing procedure. Spurious effect of particle degradation in wet direct impact tests. The standard methodology for predicting the impact erosion based on Computational Fluid Dynamics: calculation procedure, main assumptions, and their consequences. Origin and application of erosion models. The erosion model by Oka and co-workers. Notes on the sources of uncertainty of the erosion predictions. Detailed analysis of the main flaws of the standard methodology for CFD-based erosion prediction (dilute flow, steady-state assumption, point-particle approximation, uncertain applicability of erosion models) and recent attempts to overcome them.

Foreseen learning outcomes

- Recognize the engineering relevance of solid particle erosion.
- Identify the key parameters affecting solid particle erosion and explain their role.
- Describe the different investigation methods and discuss their strengths and limitations.
- Recognize the currently open issues in solid particle erosion modelling.

The second part of the course will be dedicated to laboratories prepared by the teachers. Particularly, in two laboratories the students will simulate the turbulent slurry flow in a horizontal pipe and the erosion produced by a slurry jet. The will start from numerical setups and mathematical models already developed by the teachers, and execute the simulations critically analyzing the results by answering specific questions. The last Laboratory will consist of a visit at the Hydraulic Laboratory of Politecnico di Milano, where two apparatus for slurry erosion testing are present. The students will be provided an overview of the functioning of the two apparatus and the experimental methodology and, depending on the availability of the equipment, might also try to execute a wet direct impact test under the guidance of the teachers.

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Teaching Mix

Didactical issue type	Didactical hours
Lesson	5.0 (MOOC video lessons) 8.0 (frontal lessons)
Training	
IT laboratory	8.0
Test laboratory	4.0
Project	
Project laboratory	

Information in English to support internationalisation

Course completely offered in English.
Study material available in English.
Textbook/Bibliography available in English.
It is possible to take the examination in English.
Support available in English.

Notes about the evaluation modalities

Learning assessment will be based on:

- Attainment of the certificate released after attending the MOOC on the POLIMI-POK platform and completing the quizzes with 60% or more being corrected.
- Positive evaluation of the report in which a specific topic treated in the MOOC is analyzed in detail.
- Positive evaluation of a project developed by the students working single or in small groups (2-3 people), delivered in the form of oral presentation to the teachers and other students and of written summary report. The topic of the project and the followed methodology (e.g. conceptual/theoretical, numerical, or experimental) will be agreed with the teachers.

Professors' notes

The MOOC was developed in the context of a project financed within the “T.I.M.E. Call of Projects 2018-2019”. Coordinator of the project is PoliMI - DICA, and the other partners are Czech Technical University in Prague, University of Campinas, Xi’an Jiaotong University, and Xi’an Shiyou University.

ATTACHMENT 4: Example of debug table.

POLITECNICO MILANO 1863

Debug Table

Docente: Gianandrea Vittorio Messa

MOOC: PLF101

Lesson: 1_1_05 – The particle equation of motion

TIME	COMMENT
0:07	In the figure, "t" should not be written in bold.
0:26	Symbols "p", "f", and "m" should not be written in italic. The formula should be formatted as follows: $m_{\mathrm{p}}\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \boldsymbol{F}_{\mathrm{m}} + \boldsymbol{F}_{\mathrm{f}\rightarrow\mathrm{p}} + \boldsymbol{F}_{\mathrm{p}\rightarrow\mathrm{p}}$
0:58	Speech error. It should be: "…an application of this ***equation***"
1:32	In the figure, "t" should not be written in bold.
1:34	Symbols "p" and "m" should not be written in italic. The formula should be formatted as follows: $\boldsymbol{F}_{\mathrm{m}} = m_{\mathrm{p}}\boldsymbol{g}$
1:32	In the figure, "t" should not be written in bold.
1:54	Symbols "f", "p", and "d" should not be written in italic. The formula should be formatted as follows: $\boldsymbol{F}_{\mathrm{f}\rightarrow\mathrm{p}} = \boldsymbol{F}_{\mathrm{d}} + \cdots$
1:55	Jump in the audio: the drag ***f*** places
2:02	Symbols "f", "p", and "d" should not be written in italic. The formula should be formatted as follows: $\boldsymbol{F}_{\mathrm{d}} = \frac{1}{2}\rho_{\mathrm{f}}C_{\mathrm{d}}\left(\pi\frac{d_{\mathrm{p}}^2}{4}\right)\lvert\boldsymbol{u}_{@\mathrm{p}} - \boldsymbol{v}\rvert(\boldsymbol{u}_{@\mathrm{p}} - \boldsymbol{v})$
2:43	If possible, "unhindered fluid velocity" should appear at this point.
2:46	Symbols "f", "p", and "d" should not be written in italic. The two formulas should be formatted as follows: $C_{\mathrm{d}} = C_{\mathrm{d}}(Re_{\mathrm{p}})$ $Re_{\mathrm{p}} = \frac{d_{\mathrm{p}}\lvert\boldsymbol{u}_{@\mathrm{p}} - \boldsymbol{v}\rvert\rho_{\mathrm{f}}}{\mu_f}$
3:04	Similarly, it should be $Re_{\mathrm{p}} \rightarrow 0$
3:09	Similarly, it should be $C_{\mathrm{d}} = \frac{24}{Re_{\mathrm{p}}}$
3:28	Similarly, it should be Re_{p}
3:35	The format of the axis labels should be Re_{p}, C_{d}. Furthermore, the two text boxes should be re-sized so that they look with the same size.
4:05	There are different errors. Firstly, an "=" is missing, as well as the operator "max" after C_{d}. Secondly, the word Schiller is mispelled (it should be "Schiller"). Thirdly, the formula should be formatted as follows: $C_{\mathrm{d}} = \max\left[\frac{24}{Re_{\mathrm{p}}}(1 + 0.15Re_{\mathrm{p}}^{0.687}), 0.44\right]$

	$Re_{\mathrm{p}} < 10^5$
4:36	My elbow overlaps the word “Shiller”, which should be “Schiller”.
4:46	The formula should be formatted as follows: $\varphi = \frac{A_{\mathrm{sph}}}{A_{\mathrm{p}}}$
5:32	The formula should be formatted as follows: $C_{\mathrm{d}} = \frac{24}{Re_{\mathrm{p}}}\left(1 + A^* Re_{\mathrm{p}}^{B^*}\right) + \frac{C^*}{1 + D^*/Re_{\mathrm{p}}}$ $Re_{\mathrm{p}} < 10^4$
6:12	The vertical axis label is not visible, and the format of the two axis labels should be $C_{\mathrm{d}}(-)$ e $Re_{\mathrm{p}}(-)$
6:32	The format should be: $\boldsymbol{F}_{\mathrm{b}}$ $\boldsymbol{F}_{\mathrm{b}} = -\rho_{\mathrm{f}} W_{\mathrm{p}} \boldsymbol{g}$
6:48	The format should be: $\boldsymbol{F}_{\mathrm{g}} + \boldsymbol{F}_{\mathrm{b}} = m_{\mathrm{p}}\boldsymbol{g} - \rho_{\mathrm{f}} W_{\mathrm{p}} \boldsymbol{g} = \left(\rho_{\mathrm{p}} - \rho_{\mathrm{f}}\right) W_{\mathrm{p}} \boldsymbol{g}$
6:58	The subscript “*p*” should be replaced by “pr” (this requires recording additional audio clips). The format should be: $\boldsymbol{F}_{\mathrm{pr}}$ $\boldsymbol{F}_{\mathrm{pr}} = -W_{\mathrm{p}} \nabla p$
7:10	The formula should be formatted as follows: $\boldsymbol{F}_{\mathrm{vm}} = C_{\mathrm{vm}} \rho_{\mathrm{f}} W_{\mathrm{p}} \left(\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} - \frac{\mathrm{d}\boldsymbol{u}_{@\mathrm{p}}}{\mathrm{d}t}\right)$
8:02	The format should be: $\boldsymbol{v}(t)$ $m_{\mathrm{p}} \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \boldsymbol{F}_{\mathrm{m}} + \boldsymbol{F}_{\mathrm{f \to p}} + \boldsymbol{F}_{\mathrm{p \to p}}$
8:05	I see a strange animation in the figure color.
8:20	“quick collisions” should appear at this point.
8:22	I would a third arrow item “prolonged contacts”.
8:26	I created an animation showing a collision between two particles, but I do not see it in the video.
8:51	Words “normal” e “tangential” should be left-aligned.
8:59	I would keep the two figures with the velocities “before” e “after” the impact visible until the discussion around the “tangential restitution coefficient” is ended (say, around 9:11). Also, the subscript “n” in “e_{n}” should not be written in italic.
9:11	The formula at the bottom is mistaken. It should be e_{t} = …
9:17	Speech error. It should be “…the restitution ***coefficients***”
9:20	The sketch with the impact angle should appear at this time. Additionally, the text should be “**model by Forder, Thew and Harrison**”. Finally, for consistency with the symbol used in the last week of the MOOC, θ*w,p* should be replaced by $\theta_{\mathrm{p,imp}}$. This requires recording additional audio clips.
9:36	The symbols in the plot should be e_{n}, e_{t}, $\theta_{\mathrm{p,imp}}$. The plot title should be “**model by Forder, Thew and Harrison**” and it should be aligned in the center.