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PRELIMINARY MODEL RESEARCH ON THE PICKLING BATH MOVEMENT IN A HOT-DIP GALVANIZING PROCESS

A major problem related to the use of steel products, commonly used in the construction, machinery and automotive industries, is corrosion under the influence of the environment in which these products operate. One method of extending their working time is to apply an anti-corrosion coating in the hot-dip galvanizing process. Despite the widespread use of this method, there are still problems related to the quality of the produced coatings, process efficiency and environmental impact. Surface preparation of steel products prior to actual galvanizing is crucial to the quality of the resulting coating. A particularly important step is pickling.

The pickling process is considered as a one of the key stages in hot-dip galvanizing technology, and since this stage takes the longest to complete compared to other processes, it is a major factor that determines the duration of the entire process. It was assumed that setting the pickling bath in motion would shorten the pickling process time. The first studies concerned the analysis of the possibility of using forced flow in pickling tanks in a hot-dip galvanizing plant. A concept of such a system was proposed, numerical studies were carried out for a specific variants, and then tests were carried out on a physical model of the device. The qualitative analysis conducted allowed for positive verification of the proposed concept.

Keywords: Hot-dip galvanizing; pickling tank; numerical modelling; physical modelling

1. Introduction

Research on hot-dip galvanizing process conducted in the last few years focuses on process optimization through the integration of modern technologies [1,2] (machine learning algorithms and advanced measurement systems), modifications of alloy composition [3,4] (adding Al, Mg, Sn, Bi) for improving corrosion resistance and mechanical properties, as well as on environmental issues such as recycling and recovery of acid or zinc from by-products [5-7].

Referring the pickling bath, most research work focuses on issues such as: chemistry of pickling solutions (composition analysis, pickling efficiency, inhibitors, acid recovery); research on sludge and pickling waste; modeling of production planning processes or chemical parameters, or metal recovery and wastewater treatment technology [8-12].

Although there are also research works on hydrodynamics of the tank itself through numerical simulations (Computational Fluid Dynamics, CFD) of the acid flow and its turbulence [13], this concerns the process of galvanizing steel strip. Numerical studies focus on the velocity and turbulence fields in the acid bath, the impact of the elements motion on the bath hydrodynamics, the solution temperature gradient, and finally changes in turbulent energy and turbulence intensity. However, there is a lack of research on the flow field in tanks where the flow structure is forced by setting the liquid in motion via a system of water pumps. This is particularly true given the unique research conducted both through numerical modelling and laboratory experiments using a physical model of a pickling tank.

The lack of research conducted on physical models of pickling tanks in the publicly available literature suggests that the hydrodynamics of pickling bath is an area very poorly understood in the scientific literature. Only chemical models of pickling solutions, electrochemical models (for electrolytic pickling), and flow studies in other metallurgical processes are available, which could provide inspiration. This was also the case for the research presented in this paper.

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2. Purpose of the research

The aim of the work is to eliminate, or at least significantly reduce, the bottleneck in hot-dip galvanizing technology, which is the long-term pickling process of the metal charge. In addition to the possibility of increasing the efficiency of the entire process, in the case of tanks with such a system, their number can be reduced, which results in a significant reduction in financial outlays – less expensive tanks and a smaller amount of acid solution filling the tanks. Furthermore, forced liquid circulation process should allow the use of lower acid concentrations or extend its lifespan. This has both economic and environmental benefits.

To conduct such work, measurements conducted on a real object (in a hot-dip galvanizing plant) are rarely used; instead, they are replaced by model-based studies, particularly those using CFD. Model-based studies constitute an important cognitive method, involving the analysis of simplified representations of real systems to explain the mechanisms governing the phenomena being studied.

Models obviously have certain drawbacks, particularly simplifications. However, on the other hand, these simplifications of certain initial or boundary conditions of the model enable abstraction from secondary elements and a focus on key variables and the relationships between them, which facilitates the identification of patterns.

Numerical modeling, as mentioned earlier, is often used to study the batch preparation process prior to galvanizing. However, modeling studies also include physical models of industrial equipment. Physical models of industrial devices are real-world representations of technical objects, preserving – to a specified scale – the essential geometric and physical properties of the original. They are constructed to analyze phenomena occurring in real devices while maintaining model similarity conditions. Their scale is typically reduced, hence the need to apply appropriate flow similarity criteria, such as Reynolds or Froud.

A significant feature of physical models is the ability to conduct experiments in laboratory conditions, with controlled influences of process parameters and variables, which increases measurement precision and result repeatability. Furthermore, they enable the visualization of phenomena that are difficult to directly observe in real industrial facilities. In practice, research conducted on physical models complements research conducted on mathematical and numerical models, creating a complementary system of research tools for the design, diagnostics and improvement of industrial devices.

One of the first steps in hot-dip galvanizing technology, related to batch preparation before the actual galvanizing, is the pickling of steel elements in an acid solution. This step, in terms of its duration compared to other processes, is a factor that determines the overall duration of the hot-dip galvanizing process. Optimally shortening this process can yield tangible benefits, which is why a number of studies are being undertaken on this stage of the process. It was assumed that setting the pickling fluid (acid solution) in motion would shorten the pickling process time. Therefore, initial concepts involve model studies (numerical and experimental) of setting the fluid in motion. The research facility is a pickling tank in a 6 meter long standard .

The appropriate choice of the method to be used depends on the specific nature of the research problem. However, under certain conditions, physical modeling demonstrates methodological advantages. Physical models represent real-world processes involving matter and energy, eliminating the need for discretization of equations and simplifying mathematical assumptions. This reduces the risk of errors resulting from numerical approximations. Physical models enable natural representation of highly complex phenomena (such as turbulent flows) without the need for simplified constitutive models. A major advantage of physical modeling is the ability to visualize and analyze local phenomena (e.g. vortices, separation zones) that may be insufficiently resolved in numerical grids. The results obtained from physical models are directly measured, which increases their validation value and allows their use for verifying mathematical models. Therefore, in addition to the advantages of experimental measurements and laboratory tests, they provide great opportunities for validating individual numerical models.

It should also be emphasized that there are only few physical models of pickling tanks. There is a lack of data on this topic in the publicly available literature. Physical modeling has its limitations (e.g., the high cost of model construction and difficulties in maintaining full dynamic similarity), which is why a complementary approach is used in practice, combining physical and numerical models. This approach was applied in research on the concept of inducing motion in pickling tank bath.

3. Research object and methodology

The tests were carried out for an industrial pickling tank with dimensions 7000×1600×3300 mm, including the steel charge, which was an obstacle to the flow of liquid. Numerical simulation has been carried out using open source code OpenFOAM, while experimental studies were carried out on a physical model of an industrial pickling tank, located at the Department of Metallurgy and Materials Engineering at Czestochowa University of Technology.

In numerical simulations for walls and bottom of the tank, the stationary wall boundary condition ($u = v = w = 0$) was adopted. It was also assumed that the liquid bath level is a flat free surface, stationary wall with zero shear stresses ($\tau_{xy} = \tau_{xz} = \tau_{yz} = 0$). Liquid flows though the selected nozzles and flows out from the computational domain through other selected outflow nozzles. Scheme of the pickling tank with boundary conditions applied for numerical model is shown in Fig. 1. Additionally, the control surfaces are shown. Test calculations were performed for liquid (acid solution) different intensity of volumetric flow rate.

During the flow in the tank, turbulent flow is generated. For modeling the turbulence, the Standard *k-ε* model was used [14]. Determining the parameters of fluid movement in the boundary layer requires the use of a very dense computational grid. SWF (Standard Wall Functions) was used, which requires

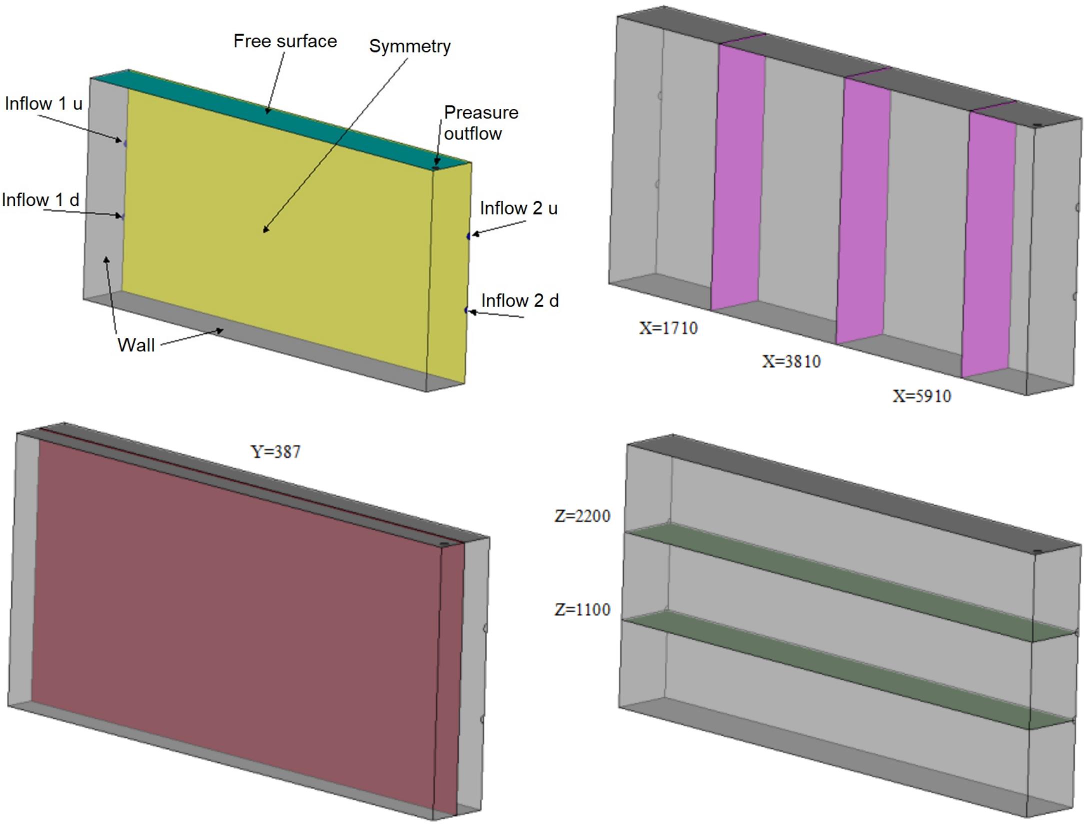


Fig. 1. Scheme of the pickling tank with boundary conditions applied and controlling surfaces

control of the y^+ parameter, which should be within the limits of 30÷60 [14].

The sequence of conducted and planned studies were as follows:

1. Modeling (numerical) studies to determine basic process parameters:
   1a. Developing the object geometry
   1b. Generating computational meshes
   1c. Developing a numerical model, including initial and boundary conditions
   1d. Conducting numerical calculations for various system configurations
   1e. Analysis of results and post-processing
2. Experimental studies using water:
   2a. Studies to determine process parameters
   2b. Studies of the flow structure in the pickling tank
3. Experimental studies using acid solution (load pickling)

4. Results and discussions

4.1. Numerical modelling results

The following boundary conditions were formulated for the simulated object: the bottom and side walls of the tank meet the conditions of a stationary wall, the upper surface was modeled as a wall with zero shear stresses. The total mass flow of the liquid supplied by the given pump system for the basic variant is 100 m^3/h. The pumps were working in the system "inflow 1 up" and "inflow 2 down" (50 m^3/h per individual pump). Calculations based on a mathematical model allowed to predict the state of fluid motion within the acid pickling tank. To emphasize the spatial nature of this motion, fluid velocity fields were determined on characteristic cross-sections, the locations of which are shown in Fig. 1. Additionally, the velocity fields were depicted on the plane of symmetry, located at the axis of the flow pumps ($Y = 800$ mm).

Fig. 2 shows the velocity change at given moments in time, presented on characteristic planes. To better illustrate the flow, the velocity scale has been narrowed to 0.5 m/s. On a global scale, for given conditions, the fluid velocity does not exceed 1 m/s. The flow structure (or rather, its changes) was observed in a spatial format. This further facilitates the observation of changes in the flow structure over time.

The measurement results visualize the fluid motion generated in the tank. Once stabilized, two characteristic currents are formed across the tank's cross-section, generating a vortex separated by the tank's axis of symmetry (height). Fluid enters the domain through the upper channel flows upward, and later, closer to the opposite wall, it flows downward and slows down as it encounters the opposing flow of fluid from the second channel. A similar phenomenon is observed for fluid entering the domain through the second channel. On the transverse planes, it can be observed that the circular shape of the inlet channel causes the fluid flow to radially spread out to the side walls of the tank. Zones with significantly lower fluid velocities – so-called "dead

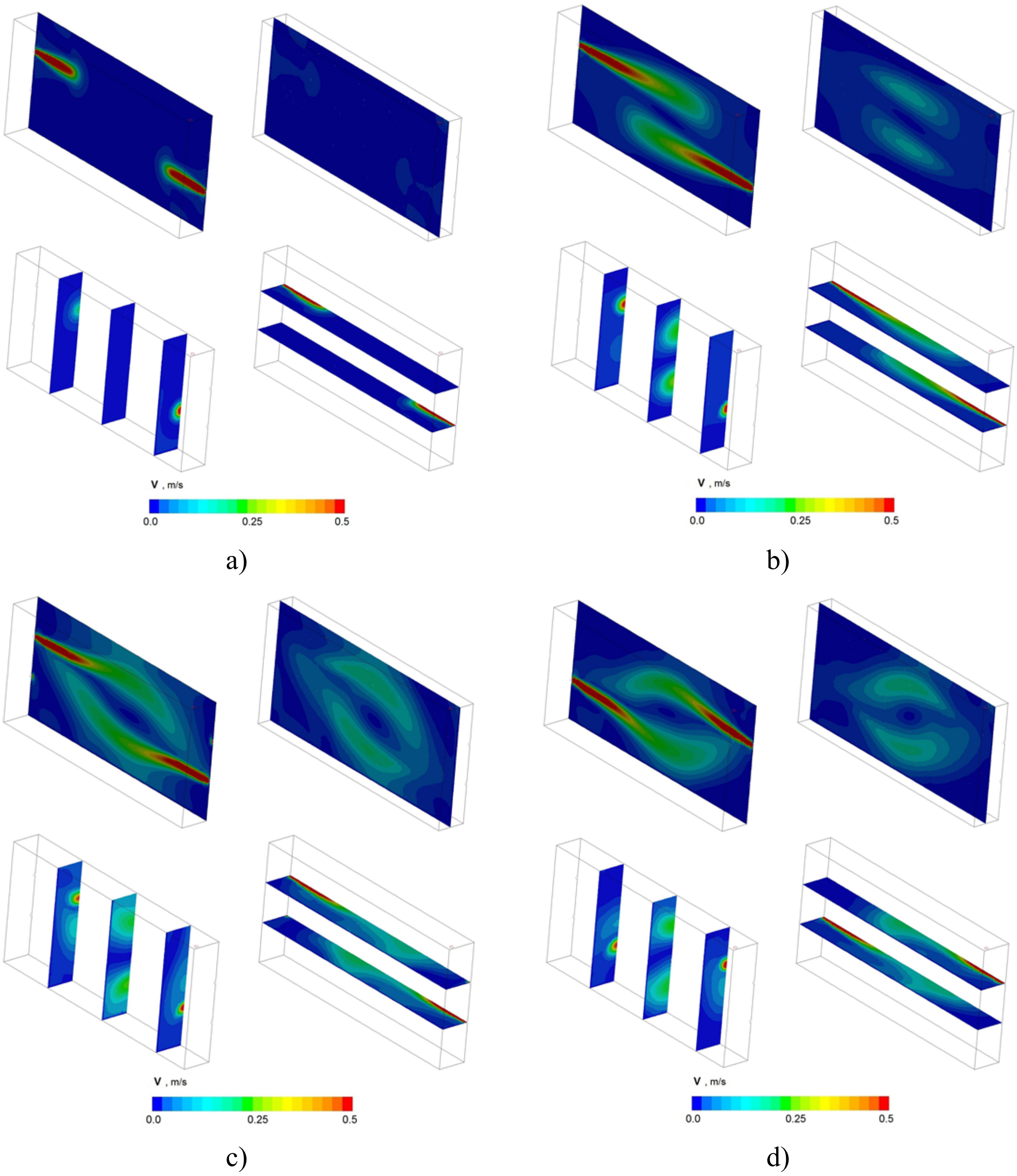


Fig. 2. Contour plots of bath velocity on the characteristic surfaces of the pickling tank after a) 10 s, b) 50 s, c) 180 s, d) 300 s

zones" – can also be observed in the tank. These are located primarily in the corners of the tank.

The numerical modelling techniques allows to understand the flow structure of liquid bath in the pickling tank and allows to determine the optimal configuration of nozzle system used to move the bath in the tank.

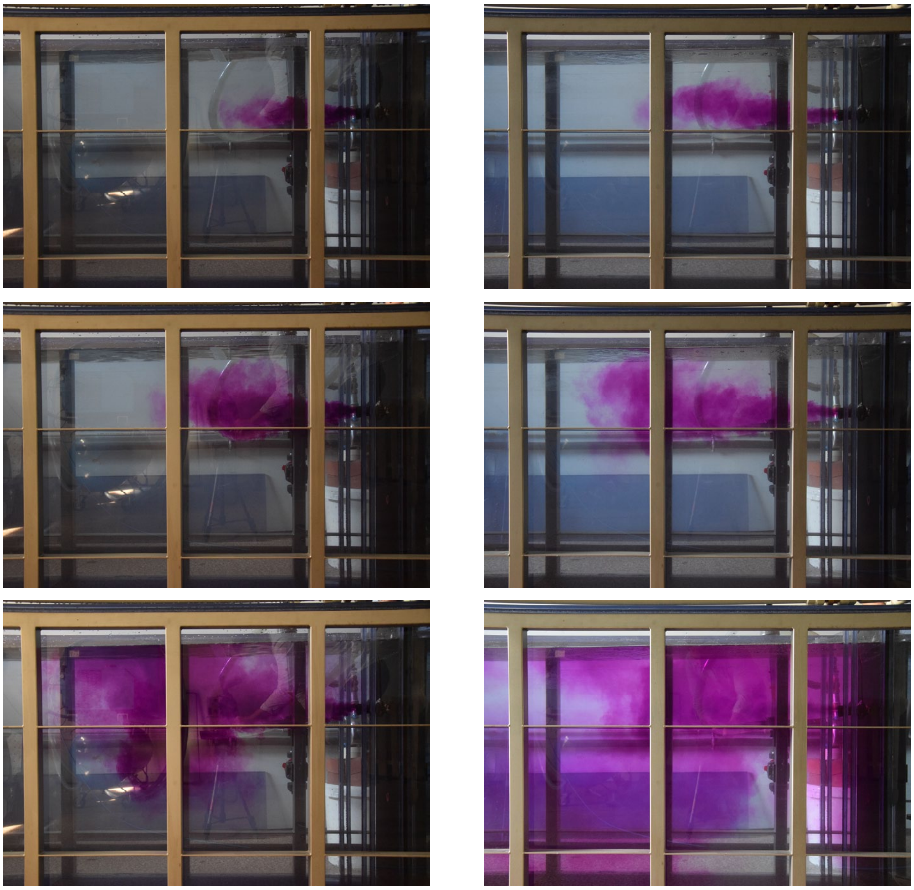
4.2. Physical modelling results

In the nex step, labortory experiments at the physical model were performed.

Based on conclusions derived from numerical studies, a proposed concept for a liquid induction system was tested on a physical (water) model of a pickling tank. Key system parameters were tested, including nozzle configuration and liquid flow velocity ranges. These studies utilized water, high-speed cameras, optical and chemical markers, and a laser, allowing for qualitative and partially quantitative flow analysis.

Preliminary studies have already demonstrated the importance of a unique physical model of the pickling tank. Research conducted on this model not only allows for the examination of the influence of individual parameters and variables on the pickling process of steel workpieces in an acid solution. Experimental measurements also provide valuable data, enabling verification of the accuracy of numerical simulations. After correct verification of the mathematical model, the numerical model can be used to further predict the behavior of the pickling bath under different configurations of the liquid induction system. Through a series of different simulations, it is possible to determine ranges of various

Fig. 3. Physical model of the pickling tank with flow control infrastructure and acid tanks (AT – acid tanks, PT – pickling tank, AP – acid pump, SSP – supply system pump, R - rotameter)



250 500

Fig. 4. Marker dispersion in selected time units, for investigated liquid flows

process parameters, thereby reducing the number of laboratory experiments. This is significant due to the demonstrated research effort, costs, and safety factors associated with laboratory tests using acid solutions.

In order to verify the CFD simulation, basic measurements at physical model were performed for unsteady conditions in order to determine the flow structure in the pickling tank after marker introduction. This experiments, as an element of qualitative analysis, allow to compare the flow especially in the first stage of the flow structure formation. Correct verification is the basis for conducting further numerical simulations for other configurations of pickling bath induction systems. This significantly reduces the need for laboratory experiments on a physical model. Proper selection of optimal configurations will also reduce the costs and safety risks associated with conducting subsequent research using a metallic charge and acid solution in the model (instead of water, which was used during preliminary flow optimization studies).

Based on the conducted research, it was clearly established that it is possible to use forced flow in pickling tanks. By appropriately controlling the parameters and process variables, it is possible to achieve the desired fluid flow structure in the tested object.

The introduction of model tests to the analysis of the steel charge pickling process also makes it possible to reduce the costs of experimental industrial research and increase research safety, while maintaining high reliability of the obtained results.

Therefore, it will be crucial to refine the system parameters and variables that determine the structure of liquid flow in the tank, such as the arrangement of channels (their height), the shape of the channels, the operating time and switching times of the system, the flow rate of the liquid through the channel (pump capacity), and determining the flow ratio through individual channels.

5. Summary and conclusions

In summary, preliminary studies, performed with a numerical and physical modeling techniques, allow to determine the flow structure in a pickling tank. Numerical modeling is effecting tool to predict flow in a tank for different forced flow system configurations. Thanks to this costs and time needed to perform experimental (laboratory or industrial) research at the early stage of investigations. Later on, tests on a physical model of the industrial device provide valuable knowledge regarding the process being studied. Furthermore, measurements on the physical model enable verification of the numerical model. In turn, using such a verified model, a series of subsequent numerical simulations can be performed for subsequent system configurations or for variable flow parameters. Therefore, using of such complementary research method (hybrid of numerical and physical modeling techniques) allows for the achievement of valuable results.

On the basis of the model (numerical and physical) tests it was found that:

– Simplifications used in CFD model do not affect the analysis of the liquid flow through the nozzles, especially at the process startup,
– Comparative analysis of the numerical simulation results with the observed marker flow during experiments using the physical model confirmed good representation of the fluid flow. The appropriate selection of the mathematical model was demonstrated, including the model describing the flow turbulence and the initial and boundary conditions of the process,
– Qualitative analysis shows, that numerical simulations using the k-ε turbulence model allow to satisfactorily predict the nature of the flow structure in the pickling tank,
– The flow structure changes with an increase in the volumetric liquid flow rate, but the maximum volumetric flow rate has to ensure that the steel charge remains stationary.

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