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Original Research Article

Development of a Model and Designing a System for Water Purification from Hydrocarbons

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ABSTRACT

This paper presents a model based on which the system for purifying water from hydrocarbons was designed with an acceptable flow and water quality for discharge into surface waters. The purification includes extracting and processing the floating hydrocarbon layer, removing the wastewater layer, and extracting soft tar. The developed system consists of two complex (sub)systems: one for conditioning floating hydrocarbons and soft tar and another for treating accumulated water. These two (sub)systems are interconnected by water and tar residue. Environmental informatics, which includes simulation modelling, systems theory, and statistical methods, forms the basis of the methodology. The result is an adaptive model for purifying wastewater to the quality required for discharge into a natural recipient and with acceptable purification dynamics.

KEYWORDS

Simulation modelling, Environmental informatics, Hazardous waste, Complex system, Adaptive model, Systems theory, Sovjak.

INTRODUCTION

Using information technology (IT), the multidisciplinary scientific field of environmental protection is expanding quickly. Exploring the intricate problems in environmental protection requires the discovery, integration, and analysis of vast amounts of diverse data. Environmental informatics converts environmental data into knowledge and information by providing methods and tools for managing it. The quality of data and research depends on information technology advancement, which also offers a solid foundation for future advancements. The simulation modelling aims to optimise the wastewater purification process and design methodology per important contaminated matter behaviour patterns [1].

The literature thoroughly describes models for presenting and analysing systems, including simulation models of discrete events, models of differential equations in continuous time,

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models of differential equations with discrete time, and operations research techniques. A dynamic approach is also used to analyse the overall behaviour of technical systems [2].

The selection of a methodology for the study and design of continuous-discrete water treatment processes is quite delicate. The process modelling approach is the foundation for system behaviour analysis, modelling, and optimisation. While modelling enables the creation of technical systems models irrespective of the variety of behaviour of their constituent parts, this method guarantees the accurate description of the system's structure, entities, and feature interactions. Other publications on this topic contain studies on model selection and process modelling [3]. Simulation modelling encompasses strategies and tactics for creating models of both continuous and discrete systems and the mechanism of moving from one component stage to the next, so it ensures that the right model design is chosen [4].

Also, simulation modelling can display the system at various levels. Conceptual models offer a presentation of the lawfulness of system behaviour and structure, thus allowing the study of the most important parameters of the functioning of the entire system or its components. Using simulation modelling, one can explore the legality of the system's behaviour, the interdependence of its entities, and the development of a system dynamics model. In this way, simulation modelling is a powerful tool for analysing the state, alignment parameters and the selection of the appropriate mode of operation of technical systems [1]. This paper focuses on modelling the purifying systems for wastewater from the oil industry.

Valuable information is obtained from using the model about the options for solving the problem, all versions of the possible solution, and potential negative impacts and states in which the system can find itself when specific characteristics of the system change [5]. Additionally, the system can be shown at different levels. Conceptual models allow the study of the most crucial aspects of how the complete system or its constituent parts operate by presenting the legality of its behaviour and structure. Simulation modelling is an effective technique for evaluating alignment parameters and the system state and choosing its best operating mode.

The complexity and quantity of data grow geometrically as the number of model elements increases [6], and the relationships between them include logical and mathematical relationships that interact [7]. The basic idea of simulation modelling is to transfer principles and experiment with objects that cannot be or would be too expensive or unethical to subject them to an experiment. The model is used to test new ideas, new scientific hypotheses or claims. Experimenting on a simulation model is, in most cases, cheaper than on a real system. In this paper, special attention will be paid to the conceptual and computational model of the wastewater purification system contaminated with a mixture of hydrocarbons, i.e. this article focuses on modelling purification systems for the wastewater contaminated with hazardous substances located in the Sovjak pit.

The Sovjak pit is a karst sinkhole with extremely steep edges (slopes), more than 30 m deep and with a circumference of around 90 m. It was used to dispose of hazardous waste, completely altering its nature over time. The county of Primorje-Gorski Kotar is where the Sovjak pit is located approximately 4 km from the sea and about 10 km northwest of the city of Rijeka, in the Viškovo municipality (**Figure 1**). The Sovjak pit is only 30 m away from the closest dwellings, and its immediate vicinity is heavily populated. The landfill is surrounded by heavily developed karst terrain, which suggests the presence of a sinkhole and deep depression with a depth of more than 40 m. The disposal of hazardous garbage in the Sovjak pit lasted more than 30 years before landfill closure in 1990.

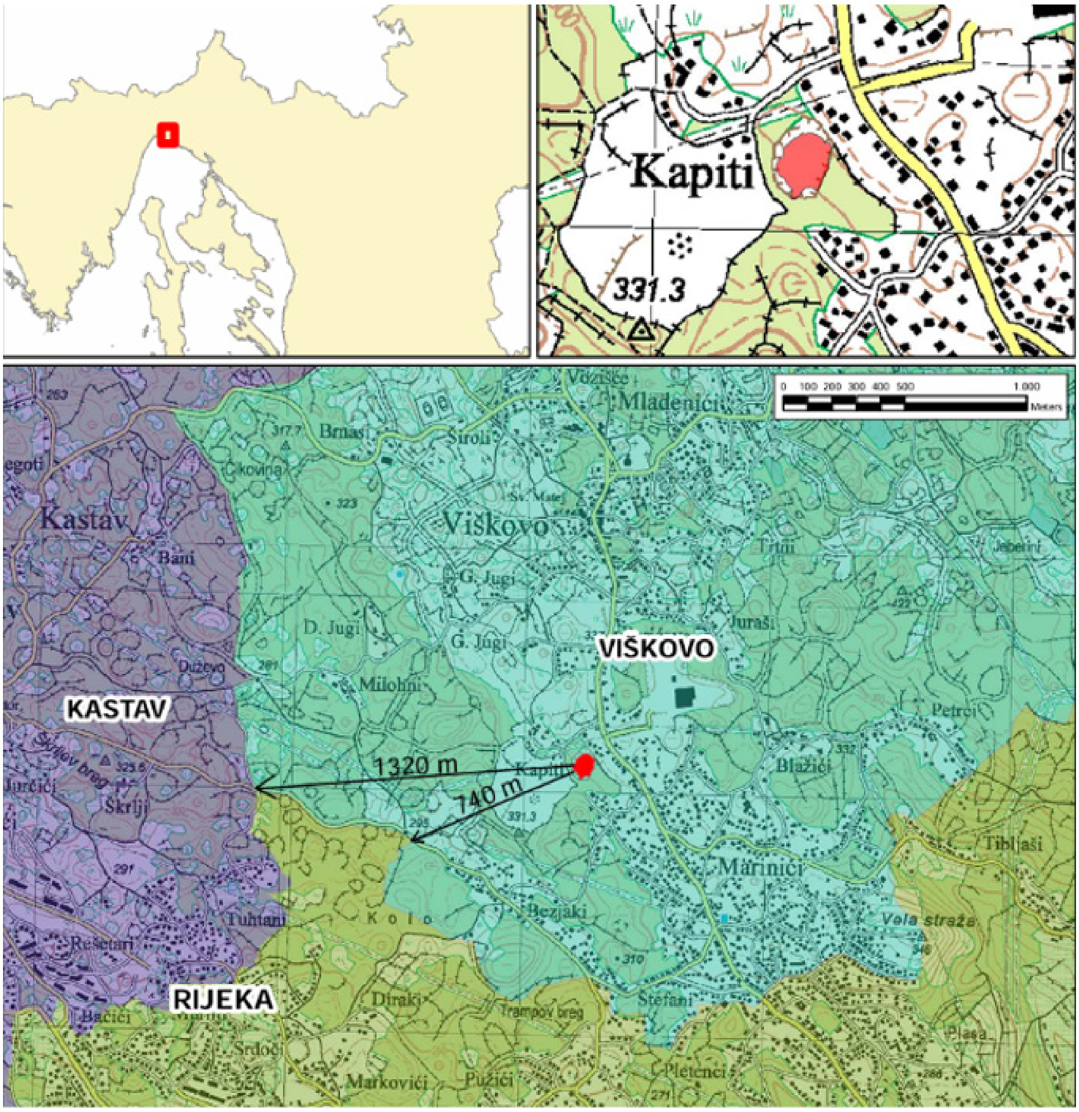
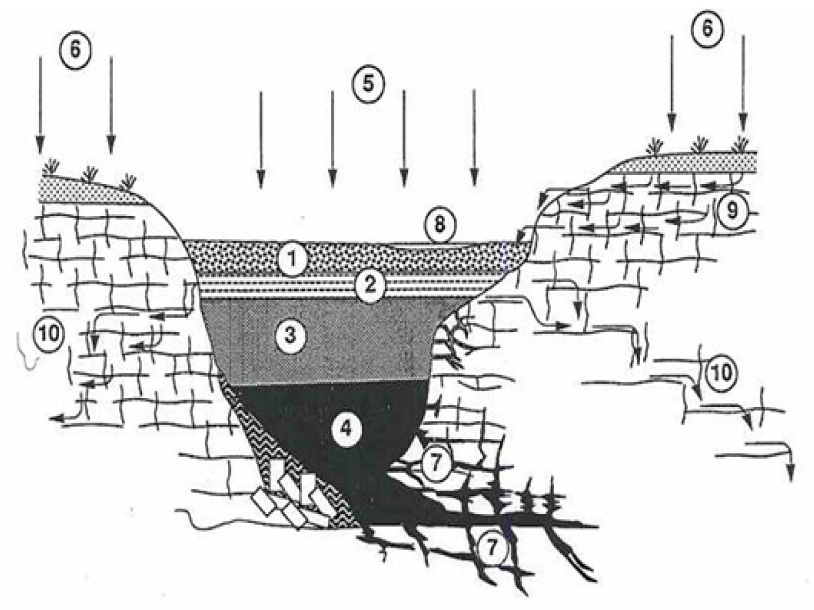


Figure 1. Cartographic representation of the location [8]

Approximately 150,000 m^3 of hazardous garbage landed between 1956 and 1990 in the Sovjak pit. For the first ten years, the Rijeka Oil Refinery in Mlaka used the landfill only to dispose of the waste tar created while producing lubricants, motor oils [9], and asphalt [10]. Tar can solidify into gudron (hard tar) because of its characteristics [11]. Later, in addition to the tar, other hazardous wastes were dumped at the landfill, albeit in much lower quantities. Coke oven tar [12], acetylene sludge from shipyards [13], crude oil and petroleum products from tanks, oil residues, other petrochemical wastes [14], wastewater from cleaning tanks, solvents, waste cutting oils [15], and subpar items from customs are a few examples of other wastes in this category. Tar fills the sink's lower portion, and a mixture of various sorts of hazardous waste is above the tar layer. Several physical and chemical processes brought about by mixing waste components resulted in the formation of multiple strata of rubbish in the Sovjak pit, each with distinct physical and chemical characteristics:

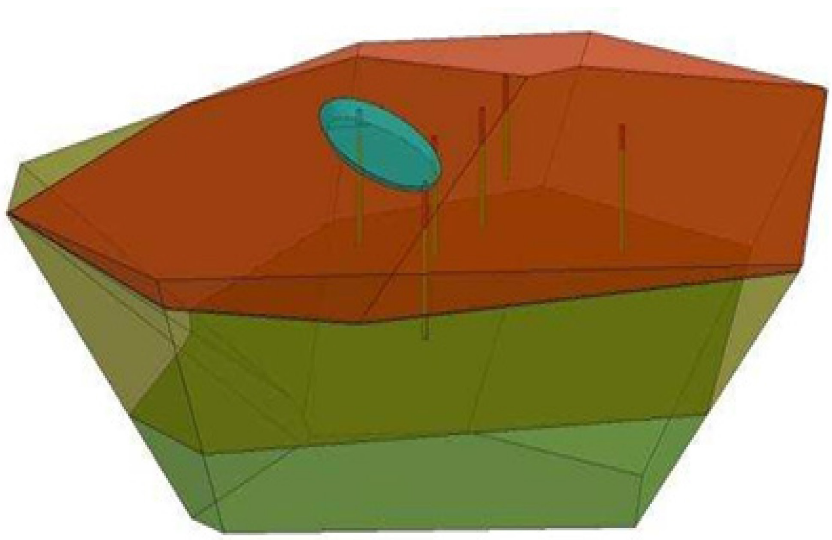
1. Layer of floating oil 7000 m^3,
2. Accumulated wastewater 15,000 m^3,
3. Soft tar and sediment 55,000 m^3,
4. Hard tar 75,000 m^3.

Figure 2 and **Figure 3** show the layers formed in the landfill, starting from its surface towards the bottom.



Legend:
1 Layer of floating oil;
2 Accumulated wastewater;
3 Soft tar and sediment;
4 Hard tar;
5 Direct precipitation;
6 Water inflow due to precipitation;
7 Tar-filled fractures;
8 Occasional appearance of a water puddle on the floating oil phase;
9 Surface inflow into a sinkhole;
10 Leach water leakage;
→ Free flow of water.

Figure 2. Conceptual model of the Sovjak landfill and the different stages of waste separation [8]



Legend:

- red – floating hydrocarbons;
- darker green – layer of soft tar;
- light green – layer of hard tar;
- blue – wastewater;
- "sticks" – exploratory wells.

Figure 3. 3D model of the waste disposed of in the Sovjak pit [8]

Industrial activities like extracting and processing fossil fuels pose environmental threats from oil pollution. When compounds tainted with oil are released into the environment, problems are caused worldwide [16]. The environmental impacts of petroleum are often harmful due to their toxicity to almost all lifestyles and may contribute to climate change. The human body is at risk from oil pollution in the air and water. A significant issue is how to remove oily effluent without harming the ecosystem [17]. Table 1 shows the characteristics of the wastewater layer.

An interdisciplinary scientific field called environmental protection significantly relies on information and communication technology (ICT) to analyse heterogeneous data and study challenging ecological problems. Simulation modelling is a standard methodology for parameterising and optimising processes [26]. Continuous-discrete water purification system analysis, modelling, and optimisation are based on describing the structure, entities, and relationships of system features [3]. As the foundation for creating a system dynamics model, mathematical models offer insight into the morality of system behaviour and the interdependence of entities [27].

Table 1. The parameters of the wastewater layer

Parameter	Value	Comment
pH	9.25–12.15	The water layer contains water with a pH higher than 8.5 and is considered basic or alkaline [18].
TDS (mg/l)	211–1889	The presence of small amounts of organic matter and inorganic salts in water is referred to as TDS concentration [19]. The materials in TDS can come [20] from human activity and natural sources, including home and industrial waste, agriculture, geological strata, and seawater. TDS in water is regulated by various criteria [21]. The ideal TDS limit for health reasons is 500 mg/L to 1000 mg/L [22].
COD (mg/l)	273–1565	Chemical oxygen demand (COD) is the quantity of dissolved oxygen required to oxidise chemical organic compounds, such as petroleum derivate, in water [23]. High COD concentrations with an alkaline pH are characteristic of wastewater contaminated with petroleum derivatives [24].
TSS (mg/l)	25–700	Total suspended solids (TSS) is the dry-weight of suspended particles that are not dissolved. TSS can also be referred to using the terms total suspended matter (TSM) and suspended particulate matter (SPM) [22].
Total oils (mg/l)	10.9–188.4	Oil-contaminated wastewater is generally treated by gravity sedimentation, coagulation, flotation, demulsification, membrane separation, flocculation treatment, chemical precipitation, biological treatment and filtration [17].
BTX content (mg/l)	0.24–0.417	Benzene, Toluene, Ethylbenzene and Xylen, collectively known as BTEX, are volatile organic compounds present in petroleum-contaminated water. BTEX compounds derived from the petrochemical industry are tenacious and non-biodegradable, which makes them particularly challenging to manage. Even in trace amounts, such compounds in the environment can harm humans and animals, including the ecosystem [25].
TOC (mg/l)	88.4–420.9	Total organic carbon (TOC) is an analytical parameter representing the concentration of organic carbon in a sample [22].

The Sovjak pit location is one of the so-called high-risk areas ("black spots"). According to the Republic of Croatia's Waste Management Strategy, such areas are highly contaminated with hazardous wastes that pose a genuine risk to public health and the environment. They were brought about by the long-term improper management of industrial (technological) hazardous waste. The Sovjak pit, a location highly polluted due to such waste, is an example of a point source of pollution that directly affects the soil pollution in the area. Polluted water seeps through the pit's walls and into the subsurface, bringing hydrocarbons to the surface in a layer correlating with the amount of precipitation that falls there each year. The local populace frequently complains about the overpowering, disagreeable smell of old, deteriorated oil, which can travel more than 100 metres on a strong wind. Furthermore, the Sovjak pit is situated in a seismically active area and inside the catchment of coastal springs in the upper section of the Gulf of Rijeka, bordering the city of Rijeka's spring catchment. It is a tectonically highly complex region with complex structural and lithological linkages, featuring various fissures and scratches in the terrain where polluted water can migrate.

Rehabilitating the Sovjak pit is crucial for the community and the ecosystem because of everything mentioned above. The model's architecture can accommodate changes in independent, dependent, and transitional variables. It makes risk prediction possible, including the identification of probable failure points of the system that could result in material loss, environmental damage, or adverse effects on human health.

Goals of the research:

1) Creating, optimising, and validating the theoretical adaptive model of a system that is "sensitive" to modifications in the operational environment,
2) Creating and verifying a model of an organic hydrocarbons-cleaning water treatment system that can be used to cleanse contaminated water before its release into the environment,
3) Developing a research technique that established the hypothesis for studying intricate engineering systems: introducing feedback from the newly created adaptive model lowers the process's variability.

METHODS

The purification of the water layer must be preceded by the extraction of solid, floating, bulky waste and the layer of floating hydrocarbons.

Waste extraction methods

Floating solid bulky waste will be collected by cranes (crane length 70 m) equipped with attachments for collecting bulky waste from the surface and the liquid mass. Floating hydrocarbons will be removed using screw pumps with an auger and a CVT system (Progressive Cavity pump), which will enable waste in a pumpable state to reach the pump body and further transport to the place of temporary storage. Due to difficulties accessing the retracted parts of the Sovjak pit, vacuum pumps and Vacupress technology will be used. The limit for applying the Vacupress system is a particle size of up to 120 mm. Heaters will be installed at the suction branch to reduce the viscosity and enable the transportability of the medium.

The pumpable waste from the Sovjak pit goes to the hydrocarbon processing device, where the first stage of waste processing and conditioning is the centrifugal separator. From it, after processing, the hydrocarbons go in separate lines to the hydrocarbon processing device for further treatment. In contrast, the separated waste water goes to the wastewater treatment device for further processing and treatment.

Accumulated wastewater previously trapped between two layers of hydrocarbons for a long time becomes homogenised with these layers. The equipment for the extraction and transport of the wastewater will be identical to that for the extraction of floating hydrocarbons.

The prerequisite for removing soft tar is to remove waste water from it for easier processing and transportation. It is a very inhomogeneous layer because it is a much stiffer waste that has already chemically reacted with tar and acetylene sludge. Due to the mentioned waste characteristics, the removal will use screw pumps and vacuum action, i.e., Vacupress technology.

Temporary storage, conditioning and on-site treatment of waste

Floating bulky waste will be stored in a tank until filled and handed over to the authorised company for the prescribed disposal procedures. Waste conditioning is required to enable safe transport. Thermal treatment will dispose of floating hydrocarbons in energy plants.

After excretion, accumulated water is transferred to the receiving pool. From there, it is sent to flocculation, coagulation, neutralisation, and equalisation in a discontinuously operated vessel equipped with a computer system for dosing coagulants, flocculants, and organic and inorganic neutralisation agents. The container (device), in addition to the dosing system for the mentioned substances, will be equipped with aeration discs, skimmers, and an analyser that will discharge the treated water into the recipient via a triple valve or in the case of insufficient quality, it will be returned to the treatment process.

Waste from wastewater treatment will join either the floating hydrocarbon fraction or the soft tar and go to incineration. For this purpose, the abovementioned device will have a transport pump to send the waste to the temporary storage location. From the device, the treated wastewater will flow to a collecting basin. A GAC (granular activated carbon) filter will be installed at the entrance to the basin. Adsorption on activated carbon (adsorbent), which in granular form can remove 75–95% of the organic materials present in the water, additionally ensures the quality of the water at the outlet.

Soft tars are very similar to floating hydrocarbons in terms of their physical and chemical state, except in terms of density and connection with inorganic and organic components from tar sludge and acetylene sludge, and the same procedures as for floating hydrocarbons are used for storage and conditioning.

In conditioning waste, especially wastewater, unpleasant and dangerous gases will develop. To collect and dispose of them properly, the vessel for homogenising floating hydrocarbons, i.e., soft tar, will have a built-in waste gas drainage system towards the scrubber. Likewise, the wastewater treatment vessel will have a vacuum waste gas collector, leading the gases to the scrubber. The scrubber will accept polluted air and purify it in a counter-current fluidising layer of water. It is important to emphasise that the scrubber must have no turbulent flow of the working medium (waste gases or water). Gases so purified can be released into the atmosphere if they meet emission limit values (ELV). If ELV requirements are not met, the gases are recycled through the blower to the scrubber. The wastewater from the scrubber is returned to the wastewater treatment vessel, where it is added to the wastewater from the Sovjak pit.

RESULTS

An object system, being a component of the real world, is described by a conceptual model **[28]**. Specifying the object system's data structure and the conditions for using the data serve as the foundation for conceptual modelling. Computer models are built on conceptual models based on ideas about the structure and logic of the system or issue being modelled **[29]**. A flowchart (**Figure 4**) and a process flow diagram (PFD, **Figure 5**) helped to develop the activity cycle diagram (ACD, Figure 6).

A flowchart is a block diagram that shows the order of choices and actions necessary to complete a process. A block for each stage in the sequence is noted. Connecting lines and directing arrows join the steps together, making it possible to view the flowchart and understand how the process works from start to finish.

A process flow diagram (PFD, **Figure 5**) is a sort of flowchart that shows how essential parts of the operation of an industrial facility relate to one another. Though its concepts are occasionally applied in other engineering activities, it is most frequently utilised in chemical engineering and process engineering to model new processes, enhance existing ones, and document existing ones.

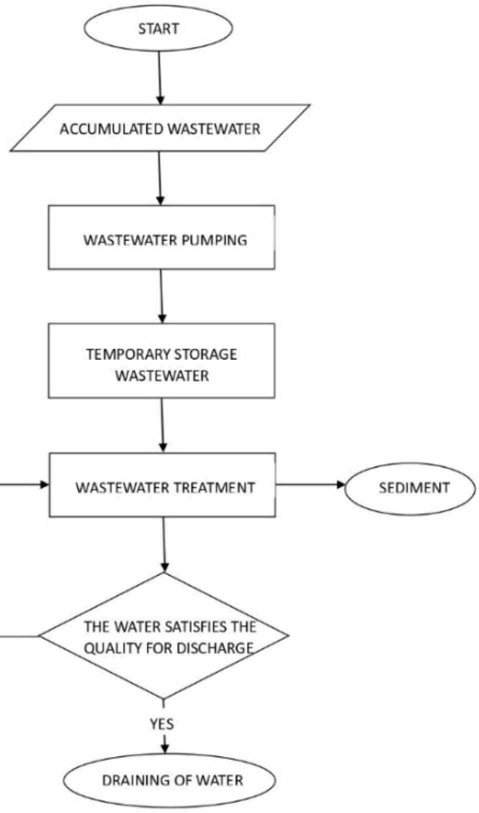
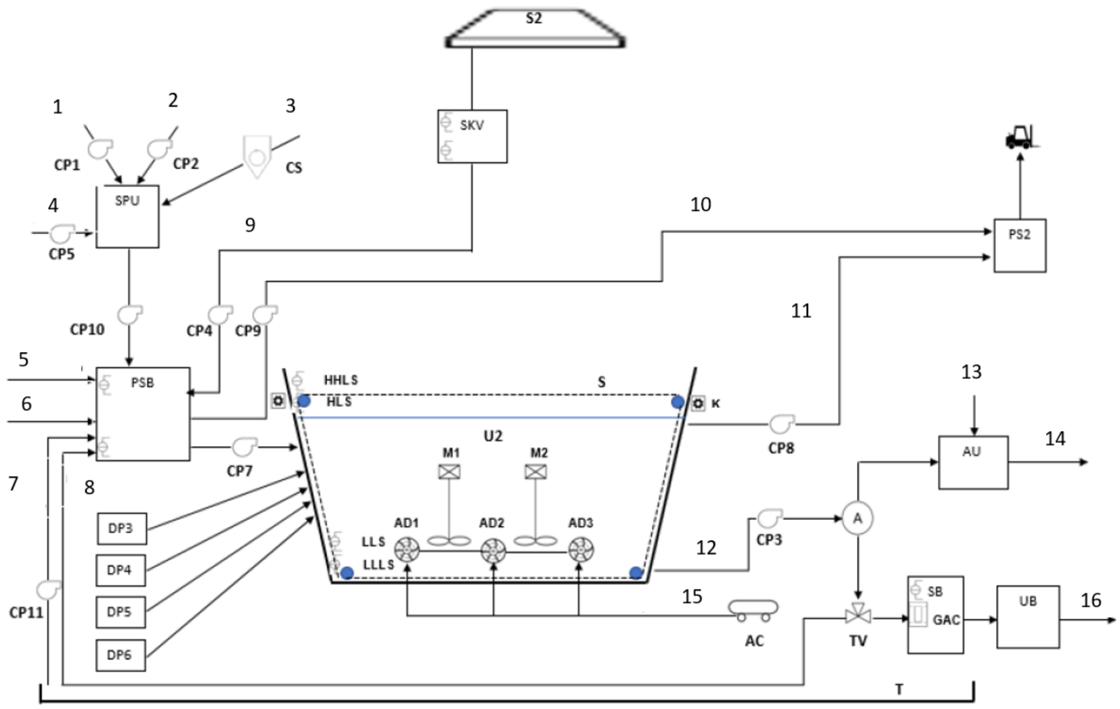


Figure 4. Flowchart of the system for purification of water from hydrocarbons (designed by the authors)



Symbol	Term	Symbol	Term
CP	centrifugal pump with capacity from 0.5 m^3/h to 10 m^3/h	1	wastewater from PK - devices for the treatment of floating hydrocarbons and soft tar
DP3	dosing pump - flocculant		
DP4	dosing pump - coagulant	2	scrubber waste water S1 - devices for the treatment of floating hydrocarbons and soft tar
DP5	dosing pump – neutralizing agent		
DP6	dosing pump – equalizer		
U2	device for treatment of accumulated wastewater with a capacity of 85 m^3	3	centrifugal separator (CS) wastewater
		4	drainage wastewater
		5	wastewater
S2	gas removal device	6	water from work surfaces
A	analyzer	7	tank wastewater
V	valve	8	unpurified water
PS2	temporary covered waterproof tank capacity 1.5 m^3	9	return of water from scrubber
		10	PSB precipitate
PSB	temporary storage - reception pool of water for purification 85 m^3	11	precipitate
		12	discharge of processed wastewater
CS	centrifugal separator	13	input signals of sensors
SPU	temporary wastewater tank	14	output signals, pumps and valves
GAC	activated carbon filter	15	compressed air
		16	discharge into the recipient

Figure 5. Process flow diagram of the system for purification of water from hydrocarbons (designed by the authors)

An activity cycle diagram (ACD, **Figure 6**), a network model of the logical and temporal links among the activities, is used in activity-based modelling to depict the system's dynamics. The activity scanning approach of simulation execution makes it simple to create an ACD **[1]**. It is a graphical modelling tool describing how items interact in a system's activity cycle and explaining action sequences to cope with various real-life situations.

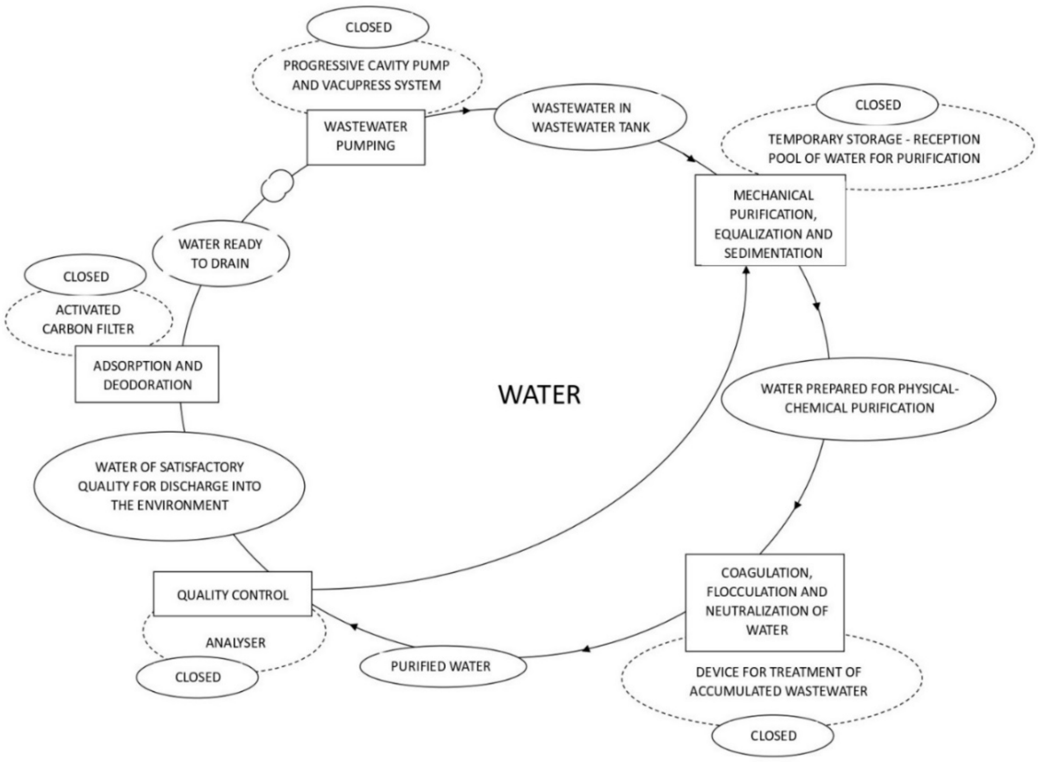


Figure 6. Activity Cycle Diagram (ACD) of the system for purification of water from hydrocarbons (designed by the authors)

Modelling the system described by all its parameters was done through multiple software systems with iteration extremes. Since the body of the device itself does not form a whole, it was necessary to model the entire system, taking account of all technical and technological parameters that affect the performance of wastewater treatment, modelling also parts of the equipment that together form one functional unit.

For this purpose, the matrix computer package MIKE3 (the sequential computer package for internal use of the MIT institute) and the final confirmation via the computer packages Hydroflow or FlowS were used. All the mentioned computer packages are considered reliable. They are widely applied when modelling various wastewater treatment devices, suitable for handling municipal wastewater and industrial effluents highly contaminated with carcinogenic compounds [30]. The calculations are based on all known postulates of fluid mechanics; that is, the ideal-fluid representation of the flowing media is abandoned in favour of the real-fluid representation.

The three-dimensional model MIKE 3 is a general non-hydrostatic numerical modelling system. The hydrodynamic (HD) module is the basic module in the MIKE 3 Flow Model. It simulates unsteady three-dimensional flows, considering density variations, turbulence including buoyancy effects, friction level and/or velocity, particle tracking, etc. The advantage of this kind of work is that it removes the error of classic calculations that are not based on 3D systems but are limited to 2D, thus increasing the error in dimensioning and design [30].

The experimentation with the model included studying the dependence between the flow velocity field and the shape of the distribution blades. A total of six flow deflectors/blades were placed inside the tank, three on each side of the tank, whose dimensions are 50 cm × 20 cm^2. The three most commonly used flow deflector models were analysed and compared: convex, concave, and vertical.

Partial results of flow deflector modelling are shown below. The modelling is carried out in a dynamic system, i.e., simulating the flow of wastewater inflow through 40,000 steps, where each step essentially represents 30 seconds of work. The above approach is also professionally called 40k-hm/f (40,000 steps lasting half a minute with a blocked frame). It is important to emphasise that all computer models stop iterating the results if any of the working medium's input parameters exceeds any value set as fixed (flow rate, type of material, density, temperature, system dilation, etc.). The iterative numerical modelling is performed until all 40,000 steps are correctly presented and adopted as realistic as possible. Thus, the possibility of error in the above modelling is minimal.

Figure 7. Value gradients

Figure 7 shows a legend for value gradients. Gradients show the direction and magnitude of the fastest increase in a quantity or function in space. **Figure 7** shows a colour palette that describes the listed and displayed physical parameters, with blue showing the lowest values and red showing the highest values.

Figure 8 shows the flow velocity distribution in the fluid around three blade shapes:

- Convex Blade Shape: Velocity is highest at the perimeter, decreasing to zero in the sheltered section, a stark contrast between high-speed edges and low-speed centre.
- Vertical Blade Shape: Velocity peaks at the top of the blade, then gradually decreases towards the bottom, resulting in a concentrated flow at the top.
- Concave Blade Shape: Similar to convex, velocity extremes occur at the perimeter, but the distribution is more uniform, with a smoother and more consistent flow gradient.

The graph highlights how each blade shape affects flow dynamics, with the concave shape offering a more efficient, smooth velocity distribution while the vertical shape concentrates flow at the top.

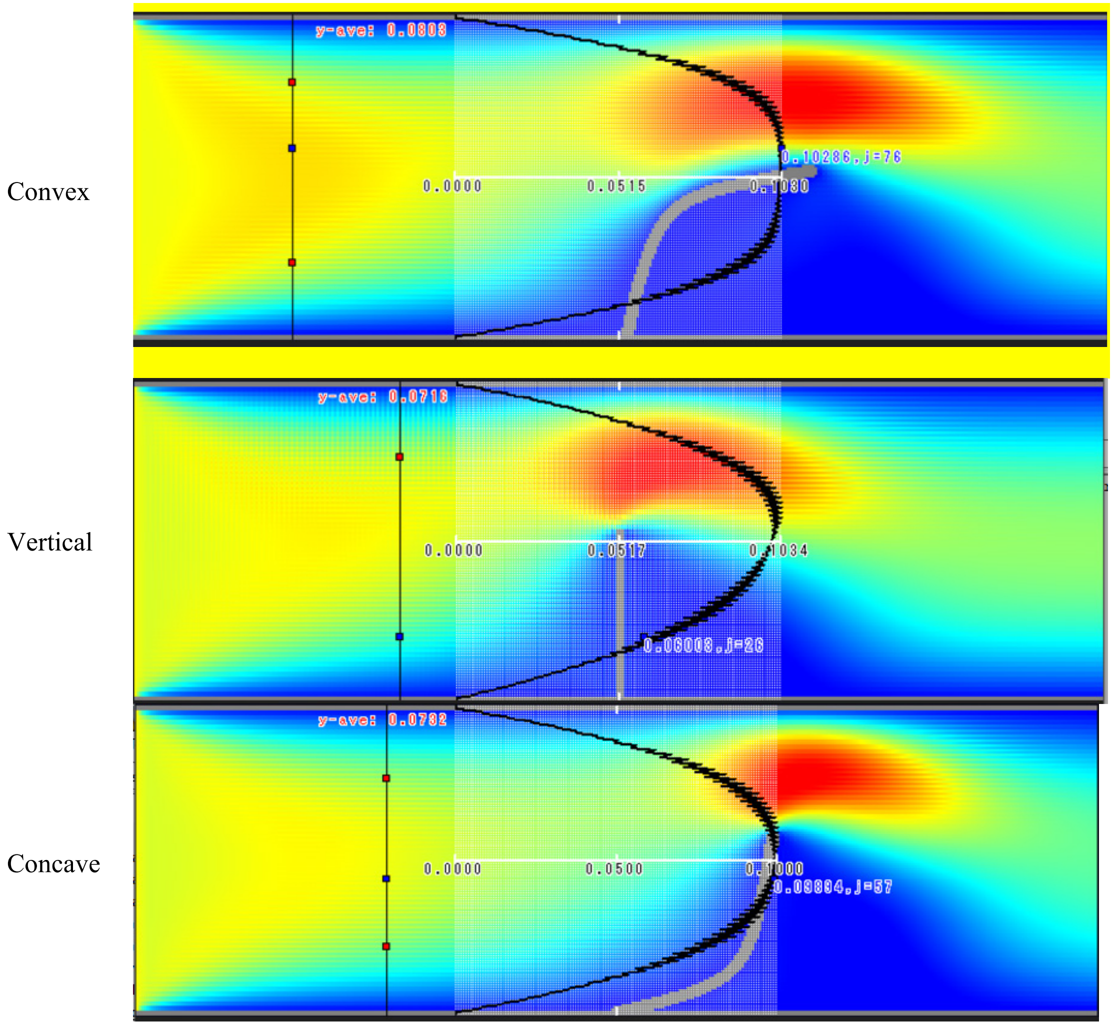


Figure 8. Flow velocity in a horizontal direction: unstable flow in two points near the blade

Figure 9 shows the flow velocity distribution in turbulent flow for three blade shapes:

- Convex Blade Shape: Velocity dissipation is highest at the perimeter and end, leading to increased turbulence and reduced flow efficiency.
- Vertical Blade Shape: Similar to the convex shape, distribution is more concentrated at the edges; a smoother transition to lower velocities offers slightly better flow control.
- Concave Blade Shape: Dissipation is more evenly spread across the flow guide, reducing turbulence and suggesting more efficient flow control than convex and vertical shapes.

In summary, the concave shape offers smoother and more efficient flow control, while the convex shape shows higher turbulence and energy loss.

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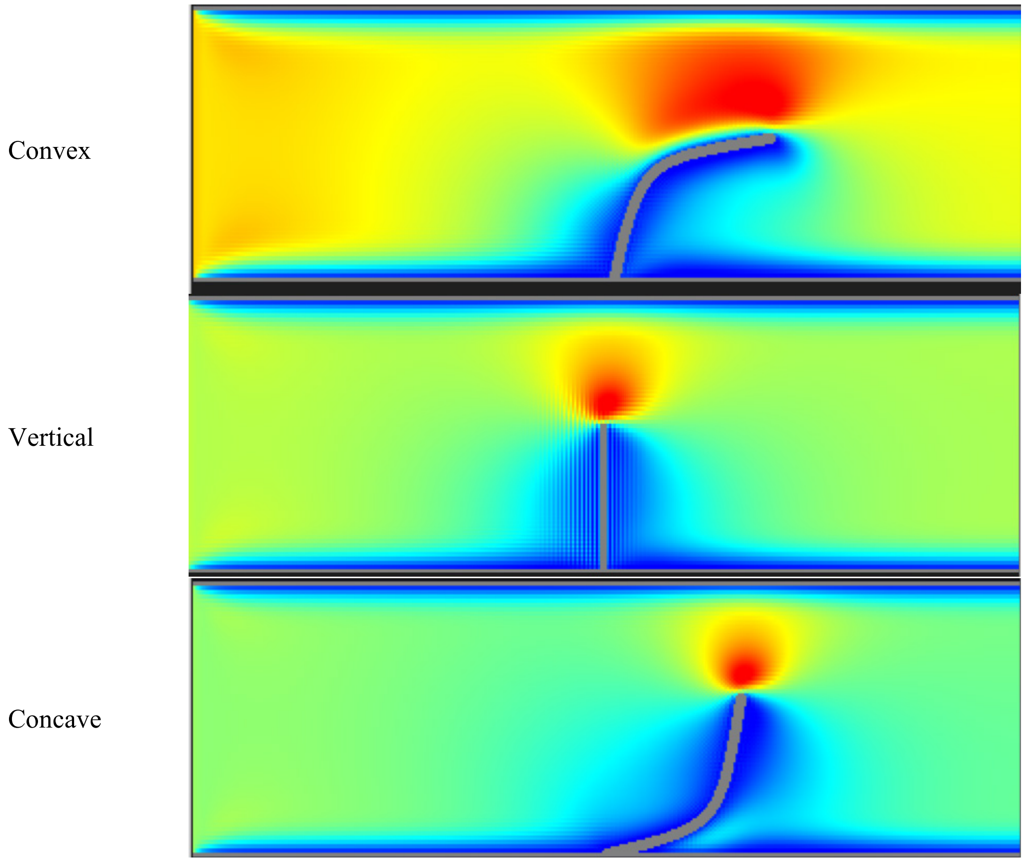

Figure 9. Flow velocity in a horizontal direction during unstable flow

Figure 10 shows the flow behaviour for three blade shapes (convex, vertical, and concave) under minimal laminar flow conditions.

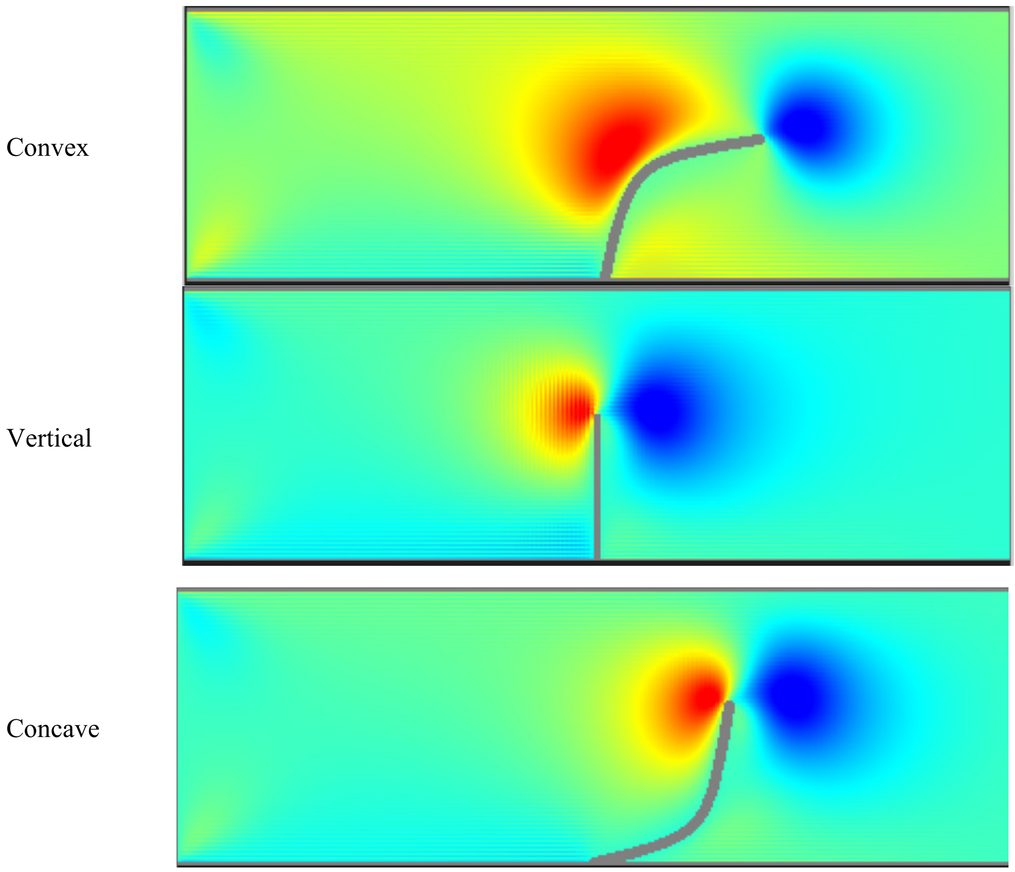

Figure 10. Flow velocity in a horizontal direction during stable flow

Figure 11 illustrates the differential pressure across the cross-sections of the flow guide for three blade shapes:

• Convex Blade Shape: The pressure distribution shows significant differences at the perimeter, leading to higher pressure losses in the flow guide.

• Vertical Blade Shape: Similar to the convex shape, with pressure variations concentrated at the edges, but with a somewhat smoother pressure gradient.

• Concave Blade Shape: The concave shape provides a more uniform pressure distribution across the entire flow guide, resulting in more efficient flow control and lower pressure losses.

The concave blade is chosen due to its more consistent pressure distribution, which reduces turbulence and pressure losses and improves overall flow control efficiency.

Convex

Vertical

Concave

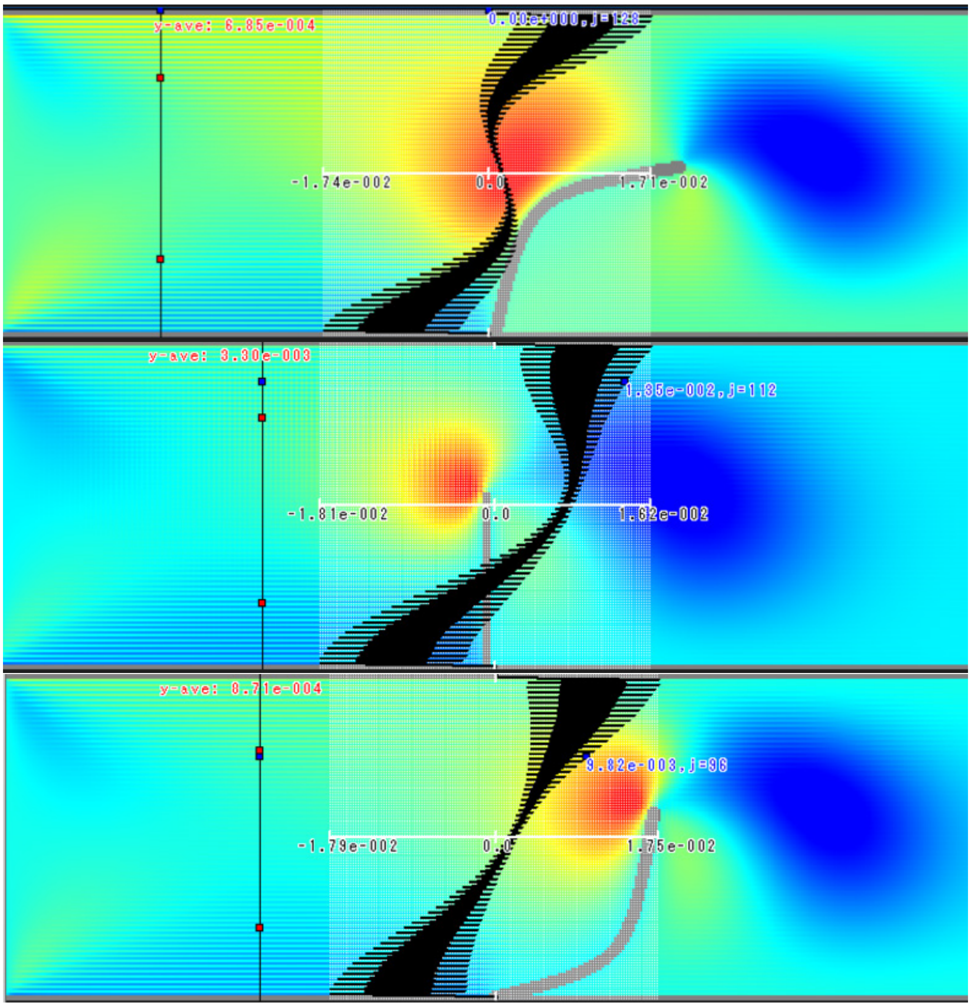

Figure 11. Pressure deviation on two selected points on the blades wall

- Convex Blade Shape: The convex blade causes a rapid velocity increase at the perimeter, followed by a sharp deceleration and stagnation at the end. This results in an abrupt change in flow, leading to potential inefficiencies and turbulence.
- Vertical Blade Shape: The vertical blade shows a velocity peak at the top, gradually decreasing towards the end. The transition is smoother than the convex shape, offering better flow stability, though still concentrated at the top.
- Concave Blade Shape: The concave shape maintains a more consistent velocity distribution, with a gradual increase at the top and a steady decrease at the end. This results in a smoother, more efficient flow with minimal turbulence.

In summary, the concave blade offers the most stable and efficient flow, while the convex shape shows sharp velocity changes and potential inefficiencies. The vertical shape provides a balance between the two.

Figure 12 shows the correlation of hydraulic pressure at two selected points in the medium for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The pressure curve shows noticeable deviations, inconsistent pressure values and irregular flow behaviour.
- Vertical Blade Shape: Similar to the convex shape, but with less deviation, the pressure distribution is smoother but still shows some irregularities.
- Concave Blade Shape: The concave shape offers a smooth, consistent pressure curve with minimal deviations, ensuring more stable flow dynamics.

The concave blade is preferred for its uniform pressure distribution, which leads to more efficient flow with fewer deviations, ensuring better stability and control.

Convex

Vertical

Concave

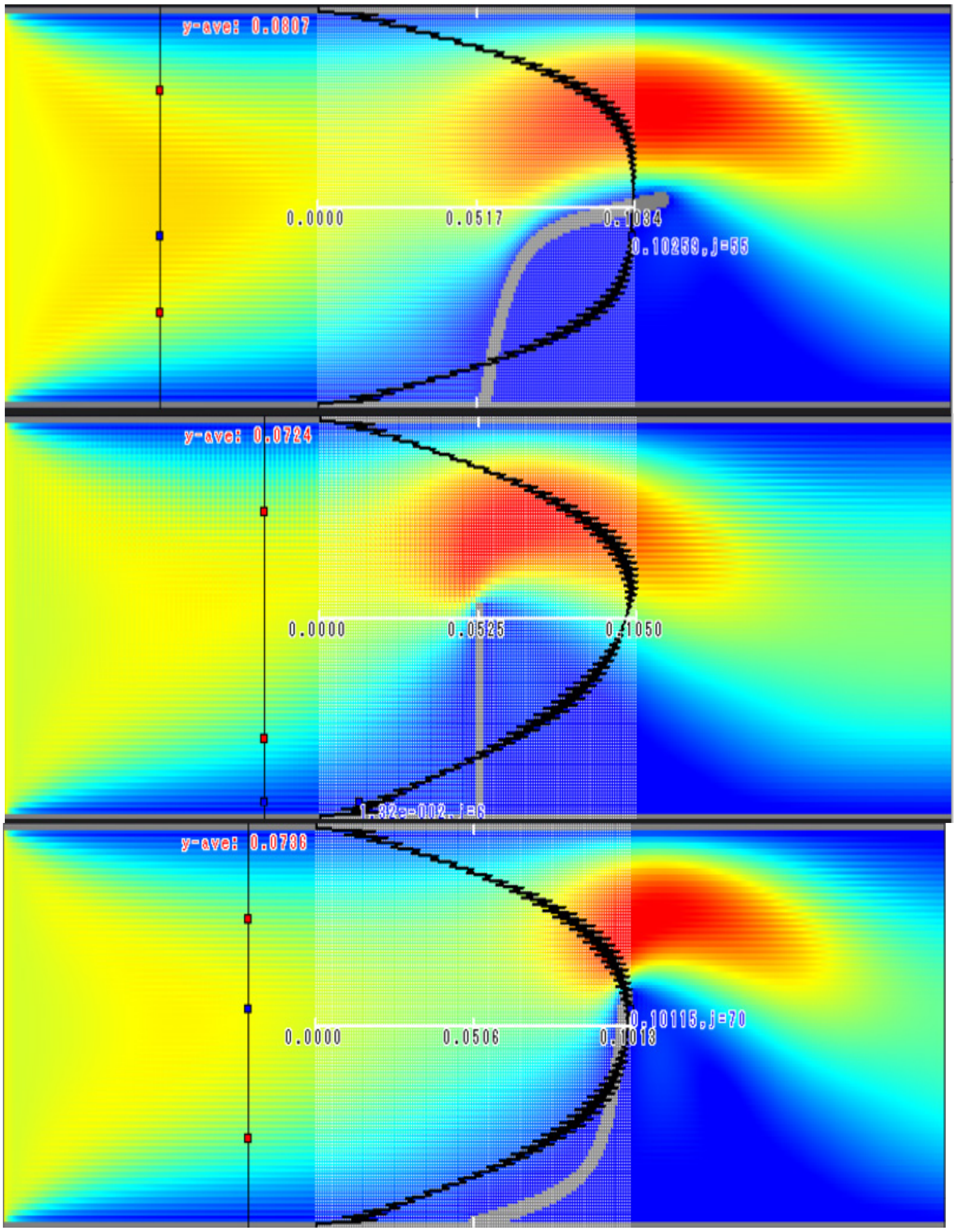

Figure 12. Pressure dispersion at the top of the shoulder blade – vector prevalence

Figure 13 shows the velocity at the perimeter of the flow guide for three blade shapes: convex, vertical, and concave, in a stable flow condition.

- Convex Blade Shape: The velocity at the perimeter is uneven, with noticeable fluctuations indicating instability in the flow.
- Vertical Blade Shape: The velocity shows a more stable profile than the convex shape but still has some fluctuations at the perimeter.
- Concave Blade Shape: The concave blade provides the most stable and consistent velocity profile at the perimeter, with minimal fluctuations.

The concave blade is chosen for its smooth and stable velocity distribution at the perimeter, ensuring more efficient and consistent flow with reduced turbulence.

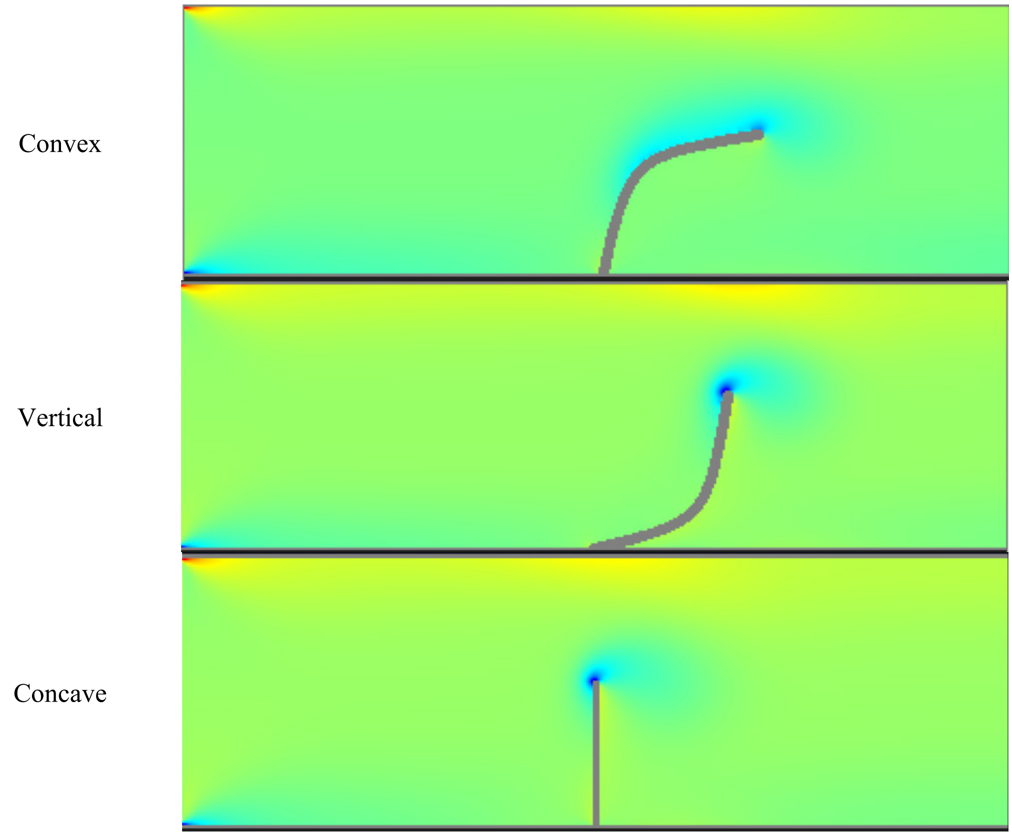

Figure 13. Displaying speed on top of a blade

Figure 14 shows the differential pressure across the cross-sections of the flow guide for three blade shapes: convex, vertical, and concave, without iterative shifts.

- Convex Blade Shape: The pressure distribution is highly uneven, with significant pressure drops at the edges, leading to inefficiencies.
- Vertical Blade Shape: The pressure distribution is smoother than the convex shape but still shows some variations and pressure losses at the perimeter.
- Concave Blade Shape: The concave shape maintains a more uniform pressure distribution across the flow guide, minimising pressure losses.

The concave blade is selected for its consistent and efficient pressure distribution, which reduces energy losses and improves overall flow stability.

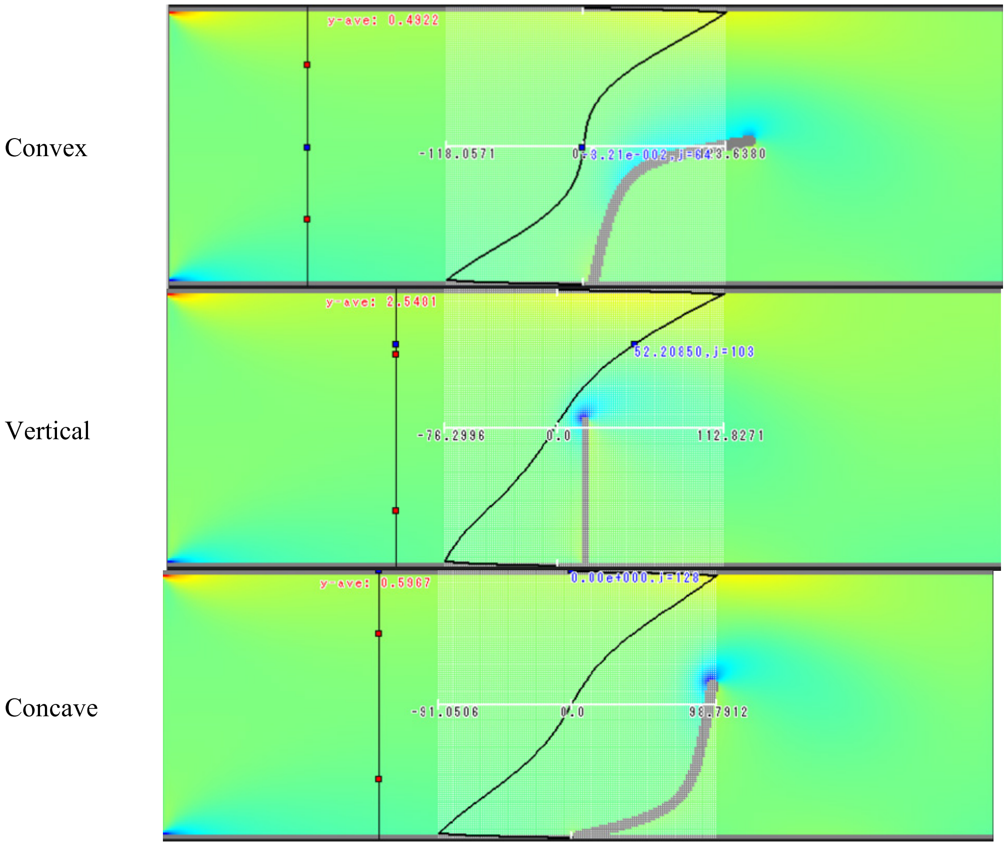

Figure 14. Differential pressure display on two allocated points on the edges of the blade

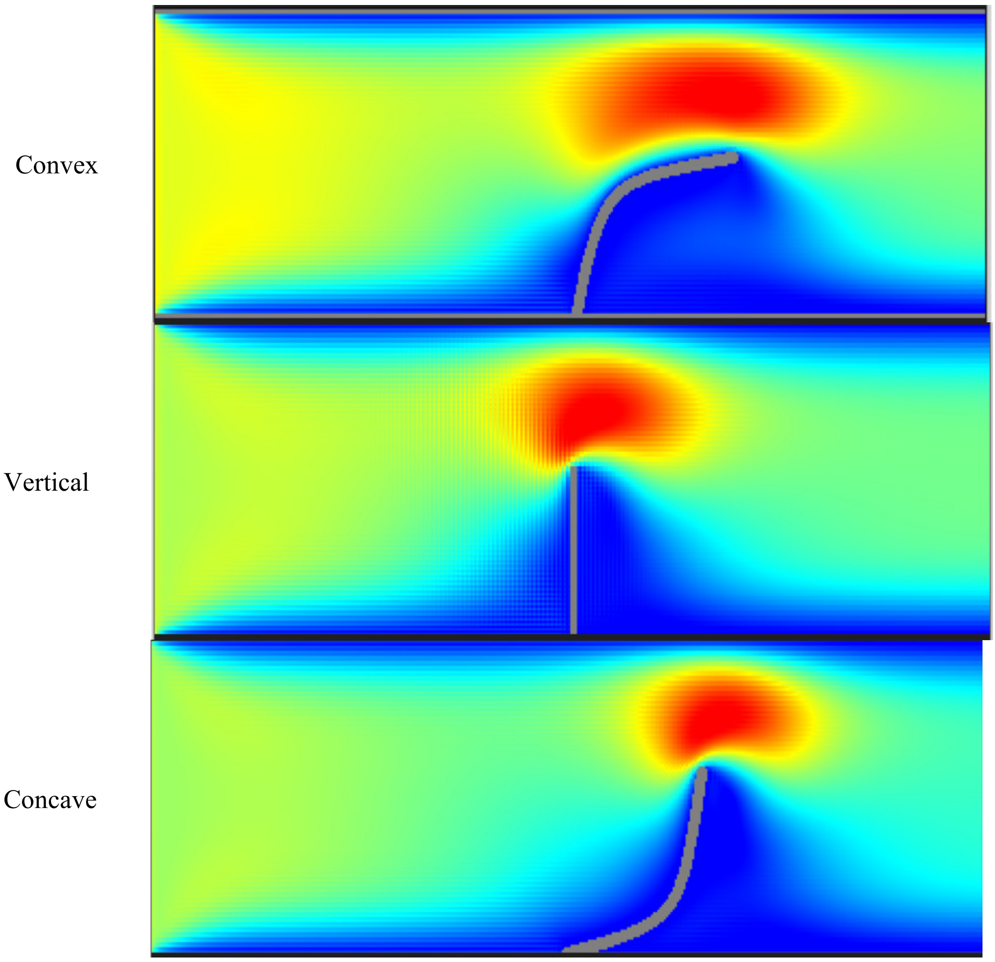

Figure 15. Display of laminar and turbulent flow to the perimeter of the blade perimeter

Figure 15 shows the velocity at the perimeter of the flow guide and the surrounding flow dynamics for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The velocity at the perimeter fluctuates significantly, indicating instability in the flow near the edges.
- Vertical Blade Shape: The velocity is more stable than the convex shape but still shows some fluctuation at the perimeter.
- Concave Blade Shape: The concave blade provides the most stable and uniform velocity at the perimeter, with minimal fluctuations.

The concave blade is preferred for its consistent and stable velocity at the perimeter, ensuring more efficient and smoother flow dynamics with reduced turbulence.

Figure 16 illustrates shock and back pressure dissipation along the flow guide for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The dissipation is concentrated at the perimeter and end of the blade, with significant pressure losses leading to reduced efficiency.
- Vertical Blade Shape: The dissipation is more evenly spread than in the convex shape but still shows some localised pressure drops at the edges.
- Concave Blade Shape: The concave shape exhibits the most uniform dissipation of shock and back pressure, leading to more efficient flow and reduced pressure losses.

The concave blade is chosen for its uniform dissipation of pressure, ensuring smoother flow, reduced turbulence, and higher overall efficiency.

Convex

Vertical

Concave

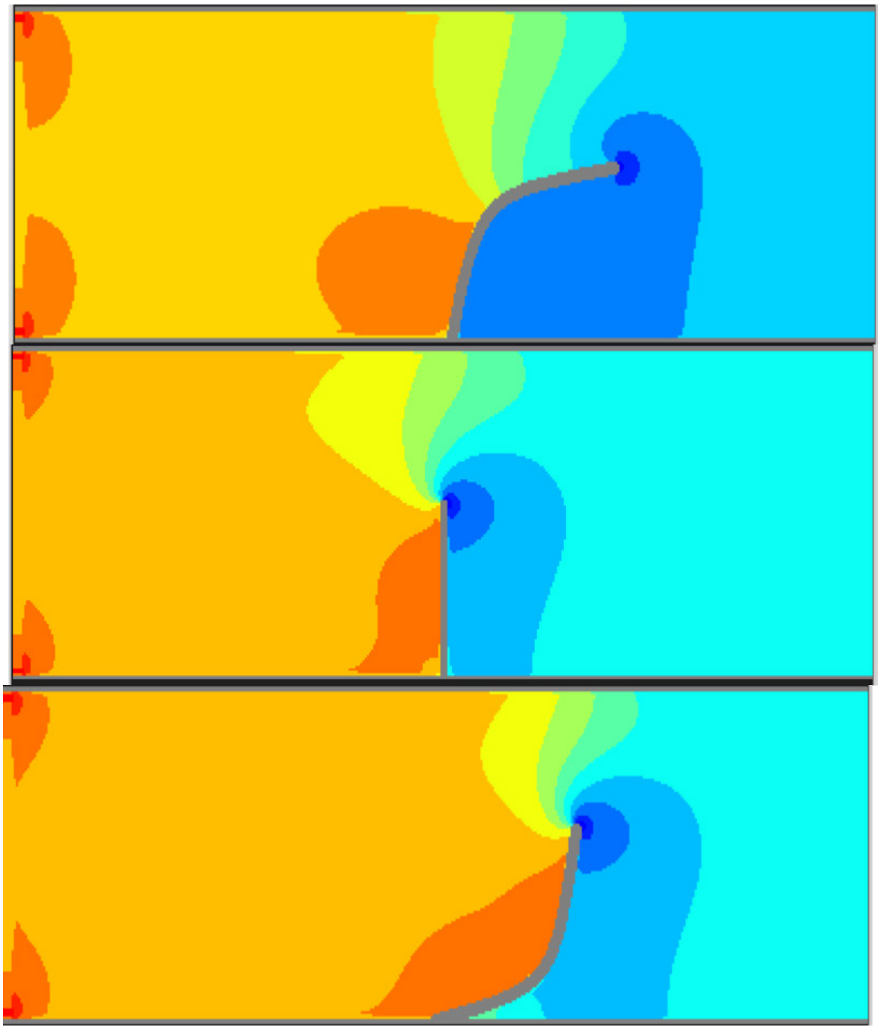

Figure 16 Display of pressure on the blade wall

Figure 17 shows the scalar velocity at the surface of the flow guide for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The velocity at the surface shows significant variations, indicating irregular flow patterns and potential inefficiencies.
- Vertical Blade Shape: The velocity profile is smoother than the convex shape, but some irregularities remain, particularly near the edges.
- Concave Blade Shape: The concave blade provides the most consistent and uniform velocity profile across the surface, ensuring smoother and more stable flow.

The concave blade is selected for its uniform velocity distribution at the surface, which ensures efficient, stable flow with minimal turbulence and energy loss.

Convex
Vertical
Concave

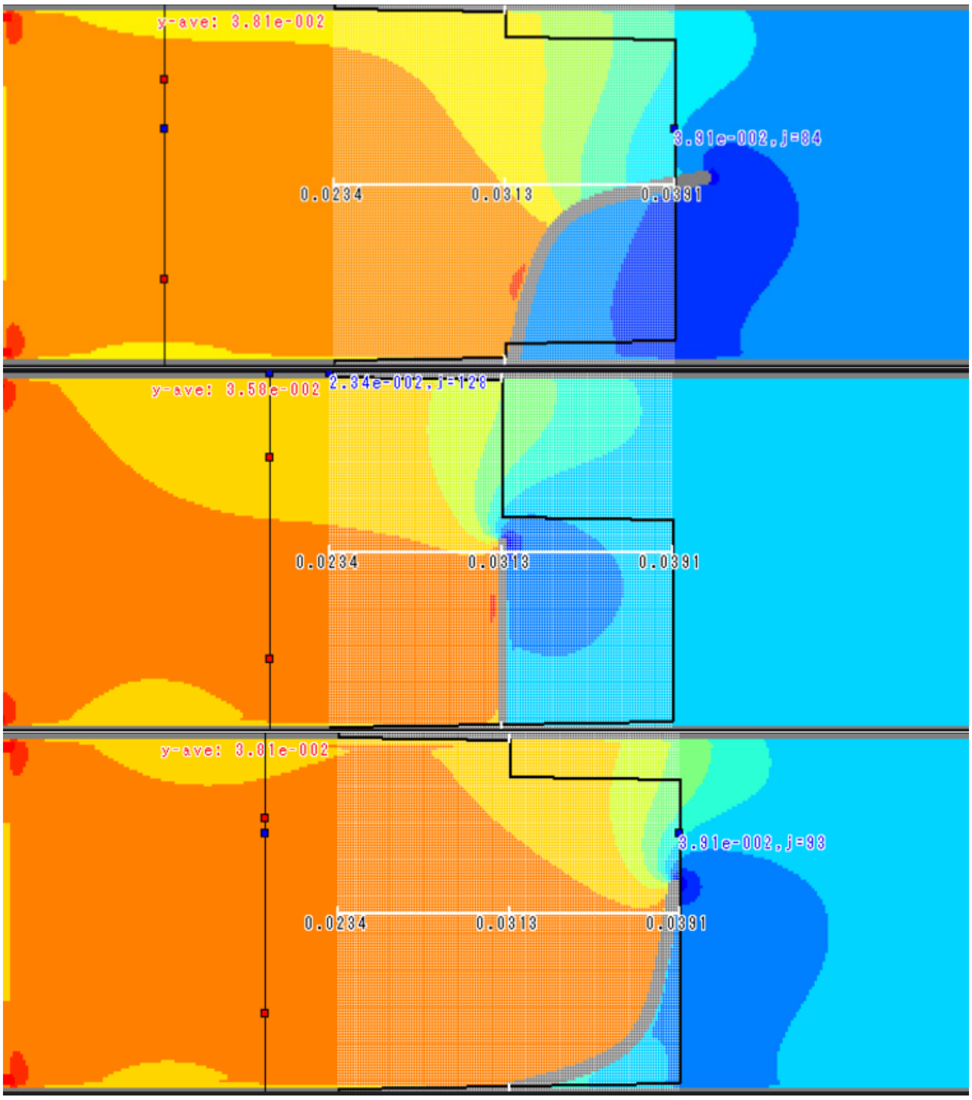

Figure 17. View of flow velocity vectors in correlation with pressure distribution at the top of the blade

Figure 18 shows the flow velocity gradient throughout the flow guide for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The velocity gradient is uneven, with sharp deviations and areas of rapid flow acceleration, leading to less efficient flow control.
- Vertical Blade Shape: The gradient is smoother than the convex shape but still shows some irregularities, leading to slight inefficiencies.
- Concave Blade Shape: The concave shape offers the most consistent flow velocity gradient across the device, ensuring more efficient and stable flow dynamics.

The concave blade is chosen for its smooth, uniform velocity gradient, which reduces turbulence and provides better flow control and overall efficiency.

Convex

Vertical

Concave

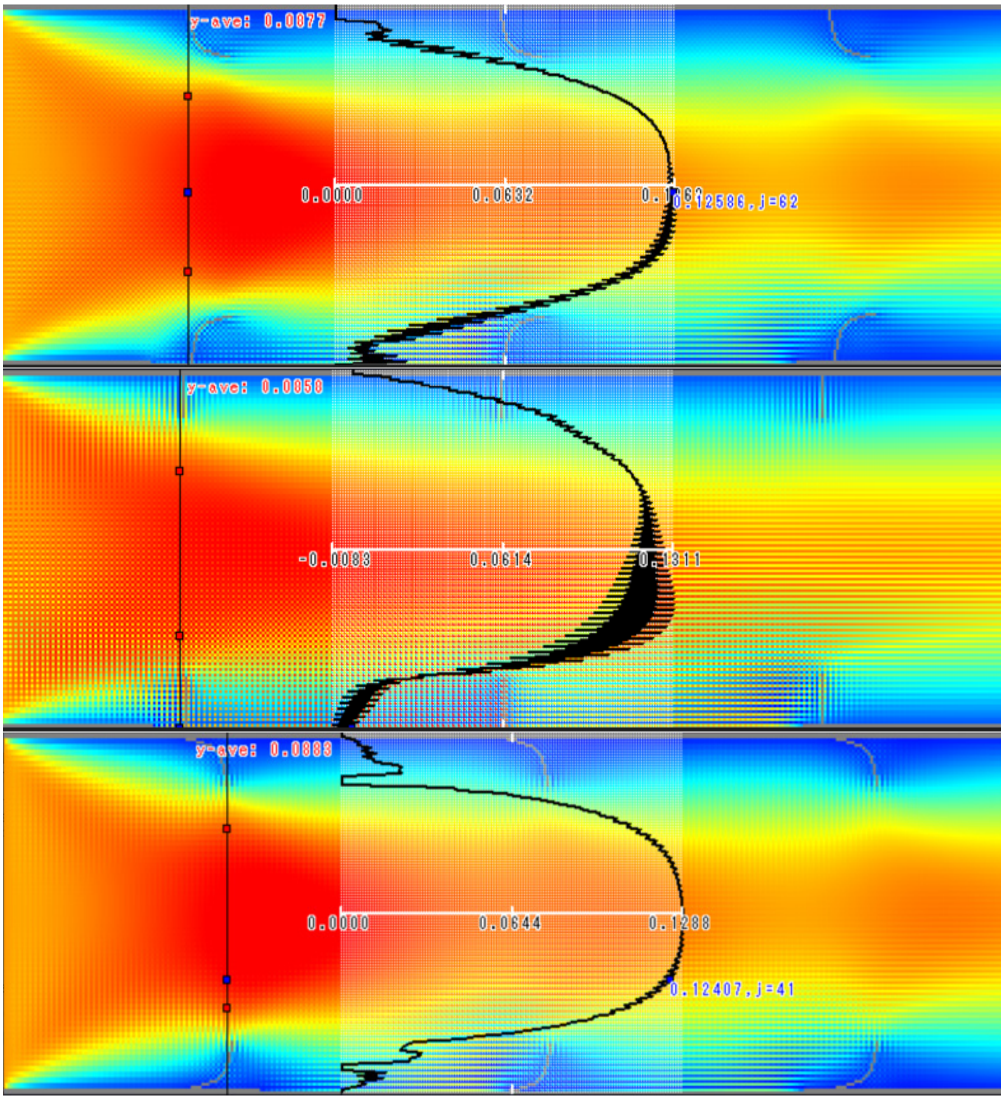

Figure 18. Flow velocity on the blade's walls in two allocated points in the medium

Figure 19 shows the combined effect of all three blade shapes (convex, vertical, and concave) on the flow dynamics within the device.

- Convex Blade Shape: The convex blades cause more localised turbulence and energy loss, with noticeable areas of disturbed flow near the edges.
- Vertical Blade Shape: The vertical blades result in less turbulence than the convex shape but still show some flow disturbances at the perimeter.
- Concave Blade Shape: The concave blades provide the most stable and consistent flow, with minimal turbulence and more efficient energy distribution across the entire device.

The concave blade is selected due to its distinct ability to minimise turbulence and energy loss, ensuring more efficient and stable flow control than convex and vertical shapes.

Convex

Vertical

Concave

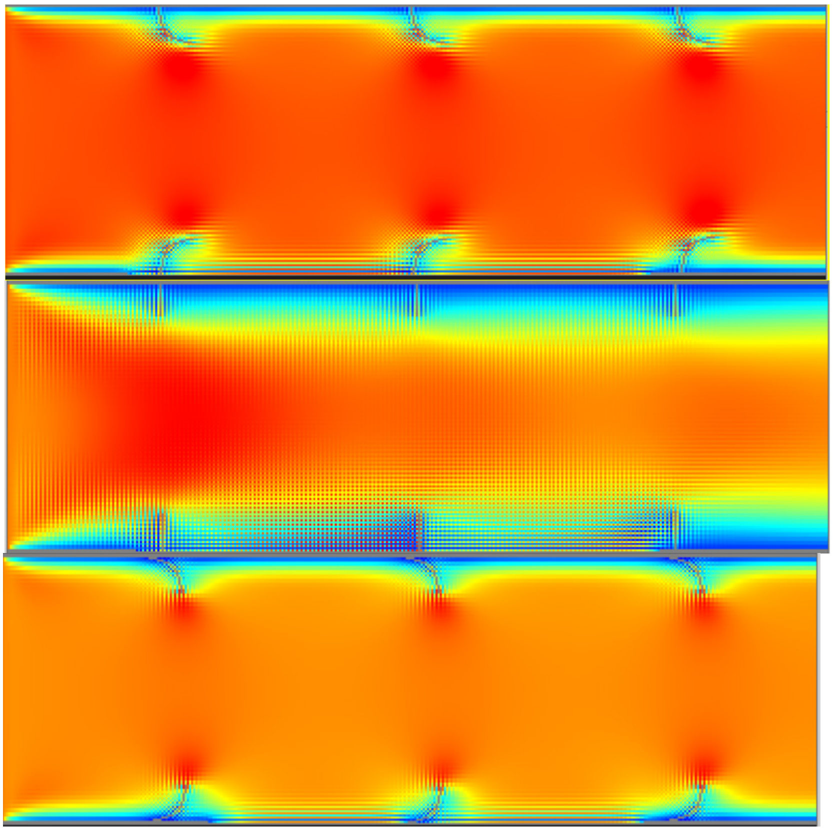

Figure 19. Flow velocity on the mixer's walls

Convex

Vertical

Concave

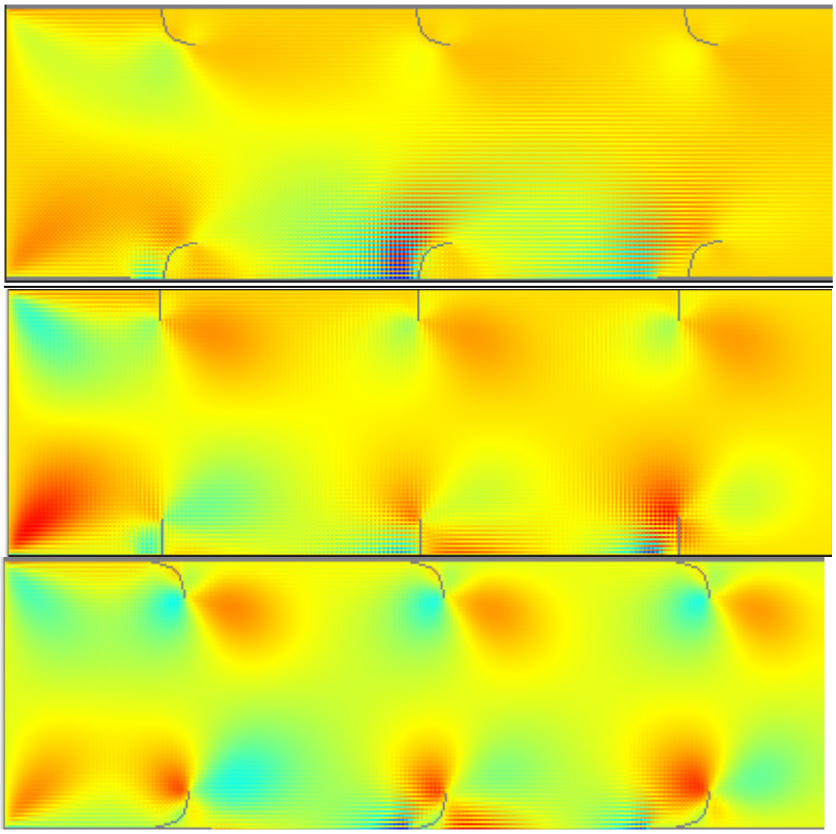

Figure 20. Flow velocity in the horizontal direction

Figure 20 shows the flow velocity along the central axis of the flow guide for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The velocity profile shows significant fluctuations, indicating instability along the axis and inefficiency in flow distribution.
- Vertical Blade Shape: The velocity profile is smoother than the convex shape but still shows some inconsistencies along the axis.
- Concave Blade Shape: The concave shape offers the most stable and uniform velocity profile along the axis, ensuring consistent and efficient flow throughout the guide.

The concave blade is chosen for its consistent velocity profile, which ensures smoother flow, reduced turbulence, and more efficient overall performance.

Figure 21 shows the projected pressures at two selected points in the flow medium for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The pressure distribution shows significant pressure drops at the edges, with noticeable asymmetry in the flow.
- Vertical Blade Shape: The pressure distribution is more balanced than the convex shape, but there are still asymmetrical pressure drops at the edges.
- Concave Blade Shape: The concave shape provides the most even pressure distribution, with minimal pressure losses and a more symmetrical flow pattern.

The concave blade is preferred for its ability to provide a more uniform pressure distribution, leading to reduced turbulence and improved overall flow efficiency.

Convex

Vertical

Concave

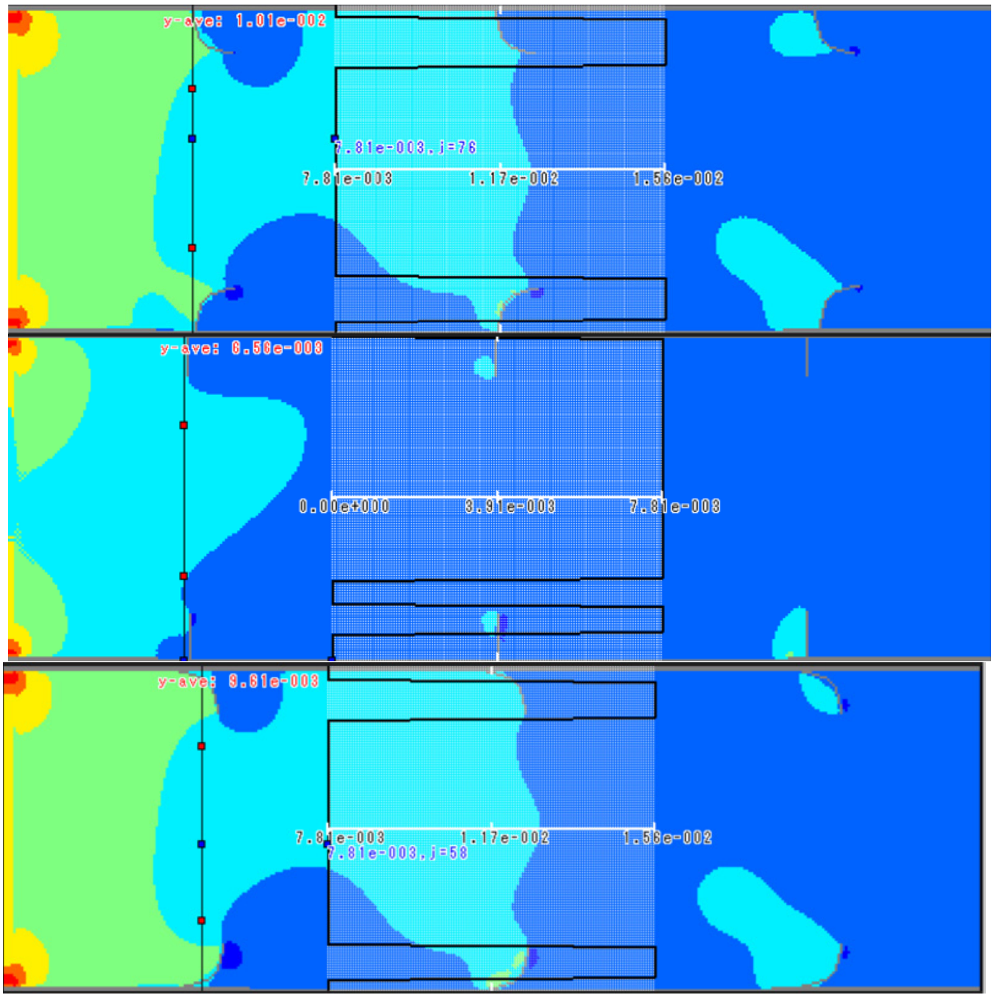

Figure 21. Differential pressures on the edges of the blade

Figure 22 shows the pressure at the edges of the blades in a steady laminar flow for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The pressure at the blade edges is uneven, showing significant pressure variation, which can cause flow disturbances.
- Vertical Blade Shape: The pressure is more uniform than in the convex shape but still shows some inconsistencies at the blade edges.
- Concave Blade Shape: The concave blade provides the most consistent pressure along the edges, ensuring stable and smooth flow.

The concave blade is chosen for its uniform pressure distribution, which reduces flow disturbances and ensures more efficient and stable flow control.

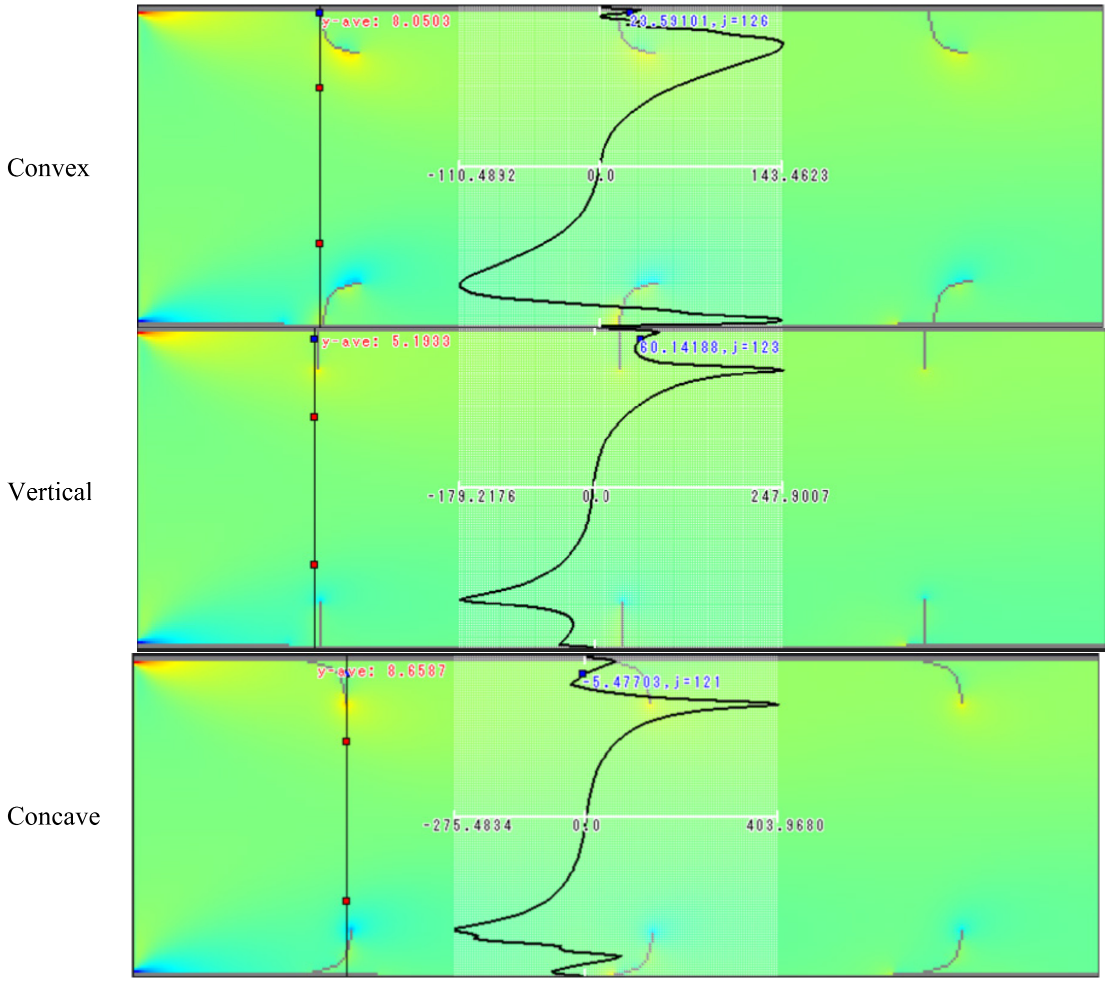

Figure 22. Differential pressures on two allocated points in the medium near the blade

Figure 23 shows the relationship between velocity and pressure within the device for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The velocity and pressure show significant fluctuations, indicating inefficiencies in flow control and increased turbulence.
- Vertical Blade Shape: The relationship between velocity and pressure is smoother than in the convex shape but still shows some irregularities.
- Concave Blade Shape: The concave shape provides the most consistent relationship between velocity and pressure, with minimal fluctuations and better flow stability.

The concave blade is selected for its ability to maintain a stable and efficient balance between velocity and pressure, ensuring smooth and consistent flow with reduced turbulence.

Convex

Vertical

Concave

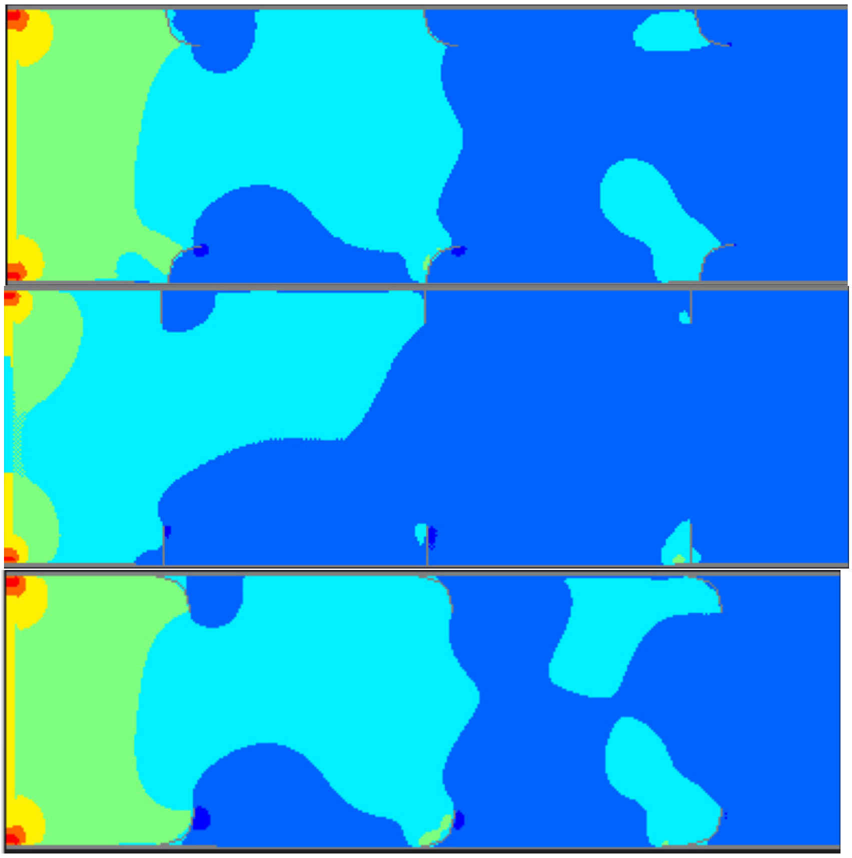

Figure 23. Flow velocity and pressure dependence in the tank

Convex

Vertical

Concave

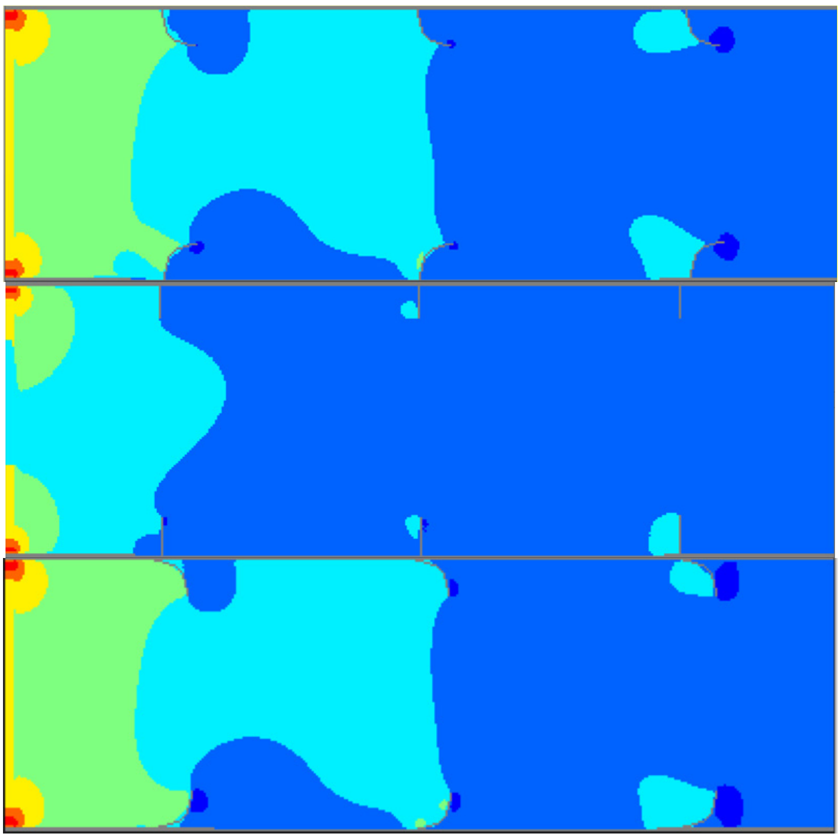

Figure 24. Pressure drops on the blade's walls

Figure 24 illustrates the pressure drops within the device caused by free flow for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The pressure drops are more pronounced, showing significant losses in efficiency due to turbulent flow near the edges.
- Vertical Blade Shape: The pressure drops are less severe than in the convex shape, but there are still notable losses, particularly at the edges.
- Concave Blade Shape: The concave blade shows the least pressure drop, with more consistent and efficient flow across the device.

The concave blade is chosen for its ability to minimise pressure drops, ensuring more efficient flow with reduced turbulence and better overall performance.

Figure 25 shows the velocity vectors at the asymptotes of the flow guides for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The vector speeds show higher variations, indicating more turbulence and inefficiency at the flow guide asymptotes.
- Vertical Blade Shape: The vector speeds are more consistent than the convex shape, but there are still some irregularities at the asymptotes.
- Concave Blade Shape: The concave shape provides the most uniform vector speed distribution, ensuring smoother flow and reduced turbulence.

The concave blade is preferred for its ability to maintain uniform vector speeds, leading to more efficient flow and minimised turbulence compared to the convex and vertical shapes.

Convex

Vertical

Concave

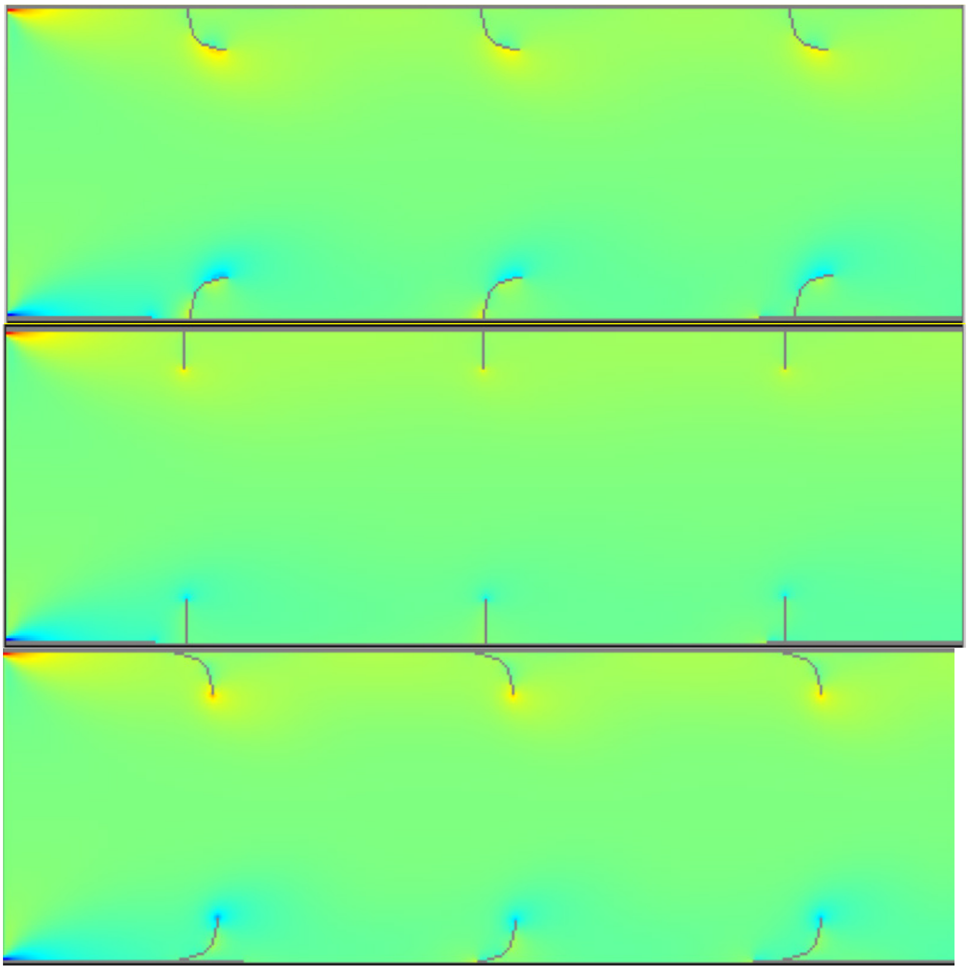

Figure 25. Flow velocity vectors on the walls of the mixer

Figure 26 illustrates the depth-wise dissipation of flow velocity for three blade shapes: convex, vertical, and concave.

- Convex Blade Shape: The velocity dissipation is uneven, with significant variations throughout the depth, leading to inefficiency and turbulence.
- Vertical Blade Shape: The dissipation is more uniform than the convex shape but still shows some irregularities through the depth of the flow.
- Concave Blade Shape: The concave blade shows the most consistent and smooth velocity dissipation, ensuring efficient flow throughout the entire depth.

The concave blade is chosen for its uniform velocity dissipation, which reduces turbulence and ensures more efficient and stable flow control across the full depth of the device.

Convex

Vertical

Concave

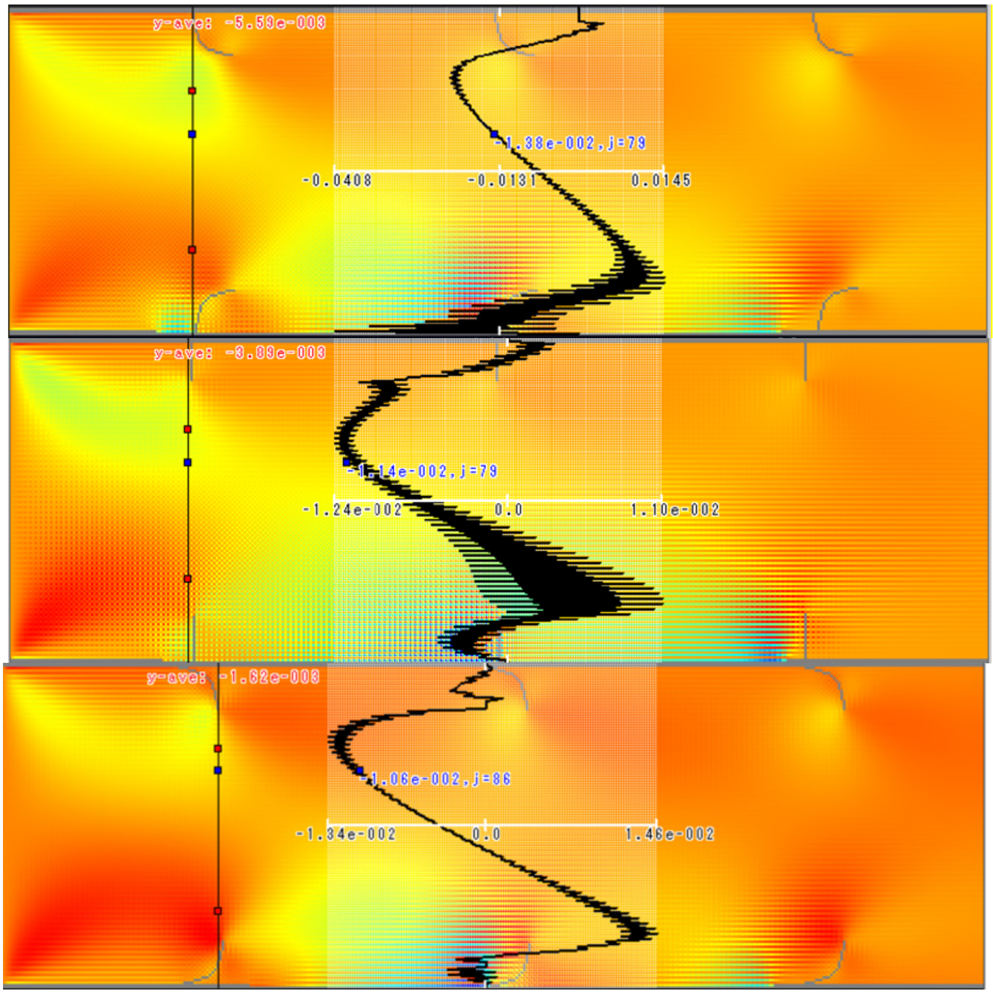

Figure 26. Vertical display of flow velocities on the edges of the blade

Based on the results from the graphs above, the concave blade shape emerges as the optimal choice for flow guidance. The concave shape consistently outperforms the convex and vertical shapes in multiple key aspects, including velocity distribution, pressure control, and flow efficiency.

1. Stable flow control: The concave shape provides a smoother and more consistent flow profile with reduced turbulence, as evidenced by more uniform velocity and pressure distributions across all graphs. This situation leads to better flow stability and efficiency than convex and vertical shapes, which exhibit more fluctuations and localised disturbances.
2. Minimised energy loss: The concave shape results in the least velocity dissipation and pressure drops, ensuring lower energy losses throughout the device. It is crucial for maintaining high efficiency in flow guidance systems.

3. Reduced turbulence: Unlike the convex and vertical shapes, which show localised turbulence, the concave blade reduces disturbances and maintains smoother flow dynamics, ensuring more effective control over the fluid.
4. Uniform performance: Across all simulations and measurements, the concave shape consistently provides better uniformity in pressure, velocity, and dissipation, making it more reliable and effective for efficient flow management.

DISCUSSION

Due to the system's complexity in purifying the liquid phase from the Sovjak pit, each device will be described separately.

Specification of the tank of the device for the treatment of accumulated wastewater

Tank U2 is made of stainless steel (inox 316). The floor plan area of the upper part of the 11 m long and 5 m wide tank is 55 m^2, and the bottom area of the 8.5 m long and 5 m wide tank is 42.5 m^2. The total height of the tank is 2.5 m, and the working height is set at 2 m. The minimum working capacity is 83.725 m^3, and the maximum capacity is 85 m^3. Due to the possible stresses in the tank's walls, it has side reinforcements. The inlet of the medium supply pipe from the temporary storage (reception pool of water for purification) and the dosing pumps in the system are placed above the tank. The medium inlet is divided into two branches due to the reduction of the incoming pressure to reduce the pressure of the supply pump.

Device for removing impurities from the water surface and sediment − skimmer

During the treatment process in tank U2, impurities gather in the foam on the water surface and sludge at the bottom of the tank. The skimmer consists of a sprocket on which support is placed at a right angle and a rubber scraper, enabling waste collection from the tank bottom and water surface. The gear shafts must extend outside the tank to the gears and chain drive, which are mounted there. The axle bearings are closed on the formwork and sealed with sealants for bearing lubrication; they must not come into contact with chemicals or water. The bearings are in closed housings on the casing of the tank. Each housing has a grease nipple for bearing lubrication. Inside the container, the chain and gears are immersed in the medium. Plates are placed transversely on that gear, and 10 cm of rubber tape is placed on the plates, which serves as a pulley. Of the four 5-meter-long shafts, two at the bottom of the tank and two on the surface. Two gears with a diameter of 12 cm are placed on each axle, on which two chains are connected by a plate, which serves as a carrier platform for rubber plates − the scrapers or the slats. Screw conveyors are installed in the side collectors, which collect waste impurities in the form of foam on the surface of the tank and sludge at the bottom of the tank and transport them to the receiving chambers. The position of the slats is vertical.

An electric motor drive is installed on the shaft, and it is also the drive assembly for the screw conveyor. The procedure takes place in one direction. Due to the choice of approach, the movement of the entire system is conditioned in the direction opposite to the clockwise direction, i.e., from right to left, looking at the diagram. The impurities collected in reception chambers are directed to the suction pipe of the centrifugal sediment pump (CP8) and the reception tank PS2. In the mentioned device, flotation or flocculation using dissolved air (dissolved air flotation) is performed as a secondary separation process to remove suspended and floating particles from water. Flotation is a process where the water phase enriched with suspended particles has a lower specific gravity than the suspension medium and is purified by floating the suspended material on the surface, where it is removed. In most applications, the effective specific gravity of the suspended phase is artificially lowered by adding air bubbles, which enables wide application in the removal of various types of suspended particles whose specific weight is greater than the specific weight of the suspension medium.

In the flotation zone, suspended substances are separated from the water. Agglomerate flocs and air rise to the surface, creating a layer of foam, and clean water remains in the zone below the surface. Likewise, due to the possible difference in polarity and zeta potential between water particles and hydrocarbons, hydrocarbons will bind to flocs and settle at the bottom due to gravity. Also, it is crucial to note that during the aforementioned processing procedures, special attention must be paid to the velocity of media movement. It must be uniform; it must not be too slow (indicatively laminar), but not too fast (avoiding turbulent motion), because otherwise it will not be possible to achieve a complete flocculent binding reaction. For this purpose, a computer model was used to determine the scalar shape and location of the blades that serve as flow breakers. For the purpose of this work, the vessel itself was modelled by defining the working volume and the shape with the aim of optimal removal of pollutants. In practice, there are several types of flocculation and coagulation devices, from vertical columns to lagoon, and in this case, a hybrid system was chosen that enables satisfactory velocities of media movement, rate of waste collection, and other parameters.

Flow diverters

Flow diverters (blades) were modelled and analysed as described in the Results section above. All three blade types are designed to achieve thorough mixing, enhancing material uniformity and process efficiency across a range of solids, liquids, and suspensions. Based on the entire model, the optimal and most functional appearance of the flow diverter was the concave shape (viewed from the direction of the media inflow), and for the purpose of further elaboration and modelling of the device, this form of the flow diverter was chosen. Likewise, in accordance with all modelling representations, it is clear that the optimal positions of the flow diverters are exactly above the aerators, which enhances their efficiency even more. Concerning the geometry and size of the device itself, six flow diverters were selected using a computer model, three on each side of the device, symmetrically placed. Asymmetric installation of the diverters would lead to turbulent movement of the medium, which would reduce the device's efficiency.

The paper presents the results of experimentation with the model relating to the selection of the shape of the blades (concave, vertical, and convex). The results can be summarised as follows.

1. Shape and design:
   - Concave Blades: Curved inward, generating high shear forces, making them suitable for mixing viscous materials.
   - Vertical Blades: Positioned vertically, promoting vertical flow, ideal for mixing bulk solids such as powders.
   - Convex Blades: Curved outward, producing a gentle, sweeping motion, which is effective for mixing liquids or delicate materials.
2. Mixing action:
   - Concave Blades: Generate significant shear and turbulence, facilitating thorough mixing of thick substances and the breakdown of clumps.
   - Vertical Blades: Create a vertical flow that ensures uniform mixing of bulk materials.
   - Convex Blades: Provide a gentle mixing action, preserving the integrity of sensitive materials.
3. Applications:
   - Concave Blades: Most effective for viscous or thick substances (e.g., pastes).
   - Vertical Blades: Ideal for blending bulk powders and other solid materials.
   - Convex Blades: Suited for liquids or sensitive mixtures where low shear is required.

Concave blades are preferred over convex or vertical blades for mixing thicker, viscous materials or when higher shear forces are needed. Their inward curvature generates high shear and turbulence, effectively breaking up clumps and ensuring a more thorough mixing of substances like adhesives or thick liquids. This design allows for aggressive agitation, reducing processing time while maintaining productivity, particularly in applications involving dense or hard-to-mix materials. Therefore, concave blades were chosen for mixing based on the need for enhanced shear and efficient material handling.

Aeration discs

The medium is aerated during the entire process with the help of porous diffusers or disc aerators. Aeration diffusers in the form of discs, domes, plates, and tubes are available on the market. Disc diffusers, especially 230 mm fine bubble discs, are common in the wastewater treatment industry. Pressurised aeration is defined as the injection of pressurised air below the surface of the water to increase the concentration of dissolved oxygen and promote the mixing of water and activated sludge in the U2 of the wastewater treatment plant. Inside the wastewater treatment device are three aerator discs connected by pipes to an air compressor placed outside the tank.

Alternative aeration devices with porous diffusers produce bubbles 2–5 mm in size. Submerged diffusers release air bubbles at a certain depth, creating a free, turbulent jet of bubbles that rises to the water's surface by the buoyancy force, with an expansion angle of 11°. The air dissolves in the water over the surface of the bubbles that travel to the water's surface. Also, air transfer is carried out across the water-air boundary on the free surface of the water due to the turbulence created by the jet of bubbles and the circulation of the water. Materials used to make diffusers can be divided into three categories: ceramics, porous plastic, and perforated membranes. Membrane diffusers are made of elastomers: ethylene propylene diene monomer (EPDM) and polytetrafluoroethylene (PTFE). The size of the membrane openings can be changed by increasing and decreasing the airflow, thus influencing the size of the bubbles.

Mixers

Two mixers for mixing the medium at 45 rpm are placed in the tank of the wastewater treatment device (U2). Mixing is to spread the additive chemicals evenly and disperse these in the processed water as effectively as possible.

Scrubber

A scrubber is a device used to remove various pollutants from exhaust gases by collecting solid particles due to the contact of the polluted gas with a suitable liquid. The exhaust gas flows in contact with the sprayed wash liquid, usually in a chamber. Creating a water curtain through which the polluted gas passes or a thin layer of liquid over which the polluted gas passes (usually water) allows the gas to exit without contaminants and pollutants that existed before exposure to the washing liquid. In the described process, solid particles bind to the liquid and grow larger, so it is easier to remove them before directing the gas to the drainage channel, i.e., the outlet. The scrubber consists of piping and a fan system that forces the gas through its chambers. The liquid sprayed through the exhaust gas collects at the bottom of the chamber.

Chemical dosing system

For dosing chemicals, four tanks of 200 l will be used to store a coagulation agent, flocculation agent, alkali neutralising agent, and acidic neutralising agent. Dosing pumps mounted on each tank will dose chemical agents through silicone tubes to U2, where coagulation, flocculation, and neutralization occur. The choice of coagulation and flocculation chemicals depends on the suspended solid to be removed, raw water conditions, plant design, and chemical cost.

Aluminium sulphate ($Al_2(SO_4)_3$, an inorganic, trivalent coagulant) and its derivatives are used as a coagulant for wastewater treatment at the location of the Sovjak pit. When added to water, highly charged ions neutralise suspended particles. The resulting inorganic hydroxides produce short polymer chains that promote the formation of microflocs. Inorganic coagulants are usually the least expensive, are widely available, and, when properly applied, are effective in removing most suspended solids. They can also remove some organic precursors that combine with chlorine to form disinfection by-products. Inorganic coagulants produce large amounts of flakes that can also "catch" bacteria as they settle and can change the pH of the water as they consume alkalinity, so the nature of the resulting complexes can be controlled using a pH system.

A chemical reaction occurs in the coagulation process, while physical interactions happen in the flocculation process. The expected result of both processes is wastewater with unchanged chemical structures of organic pollutants (hydrocarbons) because they do not react chemically but are physically bound into larger particles that settle or float depending on their zeta potential.

Chemicals based on polyacrylamide compounds are used as flocculants. Colloidal particles in surface water are negatively charged, so the water that reaches the purification device is primarily full of particles that do not settle. Because of the zeta potential of such particles and their negative charge, they cannot flocculate together unless that charge is neutralised. For this reason, positive ions in aluminium sulfate are added to the wastewater. Once neutralised, the colloid particles agglomerate, increasing the floc size. A polymer (flocculant) is added to the wastewater to enhance floc formation and hold the floc together. When the floc size becomes large enough, it settles in a settling basin.

In general, the application of the neutralisation procedure depends on the composition and quantity of wastewater, the discharge method to the wastewater receiver (continuous, occasional), and the price of the neutralisation agent. The expected neutralisation agent for use in the Sovjak pit is sodium lye (NaOH (aq)), calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$) and sulfuric acid (H_2SO_4(aq)).

Analysers

The online analysis system for water quality will be implemented by analysers with high integration features, where one set of instruments can simultaneously monitor numerous conventional indices with reliable and precise test performance. The online analyser consists of probes (sensors) for pH and turbidity, UV-VIS probes and probes for polycyclic aromatic hydrocarbons (PAHs) detection, and an analyser that collects the information obtained from the probes.

Continuous measurement of pH using online sensors is a key step in many water testing and treatment processes because a change in the pH level of the water can change the behaviour of the chemicals in the water. Turbidity sensors (turbidimeters) are online analytical instruments for continuously measuring suspended particle concentrations in various process applications; turbidity is expressed in mg/l SiO_2 or NTU units.

In addition to pH and turbidity, polycyclic aromatic hydrocarbons (PAHs) concentration will be monitored. These compounds possess the property of fluorescence − absorbing UV radiation and emitting light. The emitted light has characteristic absorption and fluorescence spectra, based on which PAHs can be detected and analysed using ultraviolet-visible (UV-VIS) spectrophotometry.

Temporary sediment tank

At the process's exit, sediment is obtained from two branches of the process, which supply sediment from PSB and U2 to pumps. The tank is made of plastic, with a capacity of 1.5 m^3. The sediment produced in the wastewater treatment process is collected in temporary storage (PS2) and taken to the hydrocarbon treatment location.

Collecting pool with GAC filter

The collection basin (SB) accepts the media after processing in U2. A GAC filter is installed at the entrance to the tank to reduce the slightest chance of harmful substances appearing. Adsorption using activated carbon is a process in which, during filtration, dissolved and colloidal substances (adsorbate) are bound to the surface of a solid substance (adsorbent) in a layer of granular material. The adsorption process can separate entire molecules or individual ions.

CONCLUSION

The wastewater treatment device for the Sovjak pit was designed using IT, specifically simulation modelling. A model was developed for this work, and a system was designed based on experimentation.

Wastewater will be pumped from the pit and brought to the reception tank (PSB). It will carry out the procedure of primary deposition of the so-called equalisation. The pre-treated water will be directed to the hybrid package unit for water treatment (U2), where water conditioning processes (flocculation, coagulation, neutralisation) will occur. Depending on its quality at the unit outlet, the treated water can be recirculated back to the temporary tank PSB or the tank SB or absorption well. The sediment from wastewater treatment will be collected in temporary storage (PS2) and taken to the hydrocarbon treatment location.

Parameters of treated wastewater will be measured at the outlet using an online analyser for continuous, real-time monitoring of water quality. It provides immediate feedback on the treatment results, enabling operators to ensure that parameter values meet regulatory standards defined by national legislation and are safe for water discharge or further use. Common parameters measured by online analysers are pH, conductivity, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), turbidity, Total Suspended Solids (TSS), and Dissolved Oxygen (DO). Measurements can also include concentrations of ammonia (NH_3), nitrates and nitrites, chlorine (free and total), Total Organic Carbon (TOC), and heavy metals − e.g., lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd).

The treated wastewater stream is discharged into the collection basin (SB), whose entrance is fitted with a GAC filter to reduce the slightest chance of the appearance of harmful substances. If the wastewater quality does not satisfy national regulatory conditions (compatible with EU legislation) for input into the SB, the stream is returned to the PSB tank for reprocessing.

The paper delineates the experimental results of the selection of blade shapes in the model. The experimentation involved concave, vertical, and convex blades, each tailored for distinct material qualities and mixing circumstances in mixing procedures. Concave blades are favoured over convex or vertical blades for mixing heavier, viscous substances and when shear pressures are required. Their inward curvature produces significant shear and turbulence, efficiently disaggregating clumps and facilitating a more comprehensive mixing of materials such as adhesives or viscous liquids. This design facilitates vigorous agitation, decreasing processing time while preserving productivity, especially in scenarios involving dense or difficult-to-mix substances. Consequently, concave blades were selected for the mixing procedures in treating wastewater from the Sovjak pit.

The research presented in this paper belongs to the interdisciplinary field of informatics and environmental protection. The environmental tests are transferred to a simulation model in different operating conditions, with the possibility of visualising and modelling the fundamental factors of the operation of a water purification system adaptable to changes and crises. Conceptualisation, parameterisation, and model development enable experimentation with no environmental consequences and optimise an adaptive water purification system that can be used in other locations and with different pollutant concentrations.

NOMENCLATURE

IT	information technology
COD	chemical oxygen demand
TSS	total suspended solids
GAC	granular activated carbon
PAH	polycyclic aromatic hydrocarbons
ACD	activity cycle diagram

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