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The Influence of Flow Rate on CIP Cleaning Efficiency and Flow Resistance in an Installation with a Three-Section PHE

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Due to the widespread application of plate heat exchangers (PHE) in the food industry, a key aspect of their operation is ensuring a high level of hygiene, which guarantees the microbiological cleanliness of the final product. This is achieved through the cleaning of installations containing PHE using the Clean-in-Place (CIP) system. An important aspect is the determination of flow resistance, as this enables the specification of drive parameters and the selection of a pump that provides a sufficiently high flow rate through the installation, particularly required during the pre-rinsing stage. The subject of the research was a three-section plate heat exchanger, which forms part of a prototype technological line designed for the pasteurisation of liquid egg mass and its fractions – egg white and yolk. As part of the study, the effectiveness of the cleaning process was assessed depending on the flow rate. Based on experimental results, the minimum flow rate necessary for effective cleaning using commercial sodium hydroxide (NaOH)-based cleaning agents was determined. In addition, the extent to which the relationship described in the literature – linking flow rate with hydraulic resistance in PHE – is confirmed under real operating conditions during the cleaning process in the CIP system was analysed. The results obtained may be used to optimise the parameters of the CIP process, which will contribute to increased efficiency, reduced consumption of chemical agents, and improved microbiological safety of the final product.

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1. Introduction

In order to maintain control over the internal cleaning process and to ensure hygiene, product quality, and safety, industrial installations are commonly cleaned using the Clean-in-Place (CIP) system [1]. A properly designed and implemented programme allows for the cleaning of elements such

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as pipelines, tanks, and plate heat exchangers without the need for disassembly [2]. The removal of unwanted solid contaminants accumulating on heat exchanger surfaces—such as algae, scale, or product residues—increases the efficiency of heat transfer through the exchanger wall [3]. As a result, this leads to a reduction in both the duration of the technological process and energy-related costs [4]. CIP cleaning is based on the principles of Sinner's Circle, which outlines the four most important cleaning factors: concentration, temperature, action, and time [5]. However, cleaning operations pose a significant environmental burden due to the consumption of chemicals, water, and energy. Engineers face the challenge of optimising the cleaning process to comply with the latest environmental protection trends, such as carbon footprint reduction. Optimisation enables a reduction in company operating costs while maintaining hygiene and product safety [6].

Plate heat exchangers (PHE) are widely used across various industrial sectors, including the food industry. Their popularity stems from a significant advantage—providing a large heat exchange surface area relative to the small volume of the device [7]. Additionally, PHEs enable the prevention of cross-contamination between fluids thanks to the use of a barrier, which is particularly important in hygiene-critical processes, as found in the food industry [8]. PHEs are frequently used for the pasteurisation of liquid food products, primarily due to their hygienic properties [9]. They consist of parallel stacks of corrugated plates, which facilitate heat transfer through increased contact surface area and significantly enhanced turbulence in the flow [10]. The plate design prevents deformation caused by pressure differences on either side of the plate [11]. Depending on the specific process requirements, various embossing patterns are used in industrial applications, each with different hydraulic characteristics [12], [13].

Heat is typically exchanged between fluids of different temperatures flowing in opposite directions, with the flow divided into multiple channels. Based on the type of connection, PHEs can be categorised into three types: gasketed, brazed, and welded.
If the process involves gradual heating and cooling of the fluid with heat recovery, several gasketed PHEs are often combined into a single multi-section unit. This configuration shortens pipeline lengths, reducing heat loss and saving space in the production area. Multi-section exchangers are particularly common in pasteurisation processes, where two or more exchangers are connected by adding additional, modified plates [14], as illustrated in Fig. 1.

An important aspect in designing installations intended to be cleaned using the CIP system is the correct selection of a pump that ensures sufficiently turbulent flow. This turbulence enables mechanical detachment of contaminant particles from internal surfaces. To achieve this, determining the pressure drop is essential [15]. In basic engineering calculations, the Darcy-Weisbach equation (Eq. 1) is commonly used to determine the resistance of isothermal flow. It describes the relationship between the pressure drop resulting from real flow Δp , the physical properties of the incompressible fluid, the channel geometry, and the resistance coefficient λ. Its main advantage lies in the fact that, under steady-state conditions, these parameters remain constant and are easily measurable, which facilitates practical application [16].

$$\Delta p = \lambda \frac{L}{D} \frac{\rho u^2}{2} \quad \text{(Eq. 1)} \quad [17]$$

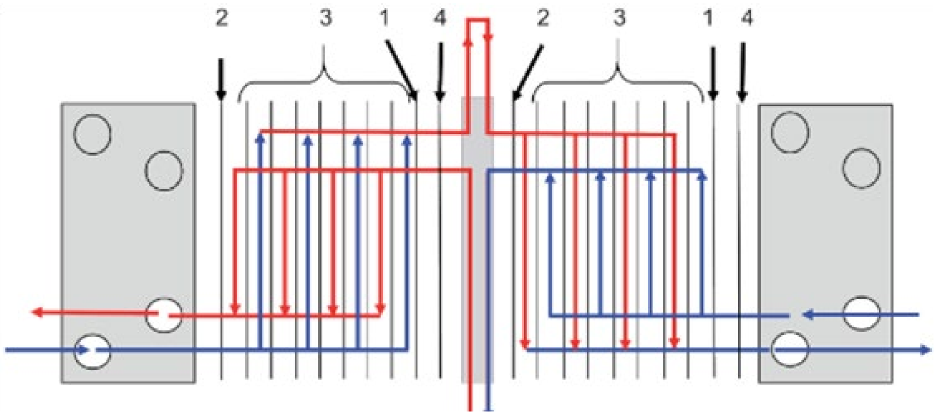

Fig. 1. Example of a multi-section set up [14]. 1 – end plate I; 2 – end plate II; 3 – channel plates; 4 – transition plate

In plate heat exchangers, the flow of fluid over corrugated plates changes direction multiple times, leading to local increases in turbulence—an effect desired for efficient heat transfer [18]. channels between plates, only to be merged again, causing continuous changes in linear velocity u. Consequently, determining the pressure drop Δp sbecomes a complex task, and significant discrepancies appear in the correlations proposed in the literature [13], [19], [20], [21] . The pressure drop in a PHE can be described as the sum of three components, as shown in (Eq. 2:

$$\Delta p = \frac{2fL_V P G_c{}^2}{\rho D_e} + 1{,}4\frac{G_P{}^2}{2\rho} + \rho g L_V. \qquad \text{(Eq. 2) [22]}$$

Where:

The first term $\left(\frac{2fL_V P G_c{}^2}{\rho D_e}\right)$, describes the pressure loss caused by flow resistance through the channels between corrugated plates, where the Fanning friction factor f is defined by (Eq. 3, and the mass flow velocity through the channel $G_C$is defined by (Eq. 4.

$$f = \frac{K_p}{Re^m}, \qquad \text{(Eq. 3) [22]}$$

where K_p and m coefficients taken from tables for the appropriate Reynolds number Re and the plate corrugation angle β.

$$G_c = \frac{\dot{m}}{bW_P}, \qquad \text{(Eq. 4) [22]}$$

The second term $\left(1{,}4\frac{G_P{}^2}{2\rho}\right)$ refers to the distribution channels, where the port mass velocity $G_P$is described as the ratio of the mass flow rate $\dot{M}$ to the cross-sectional area of the nozzle $\frac{\pi D_P{}^2}{4}$ (Eq. 5) [19].

$$G_P = \frac{4\dot{M}}{\pi D_P{}^2}. \qquad \text{(Eq. 5) [19]}$$

The third term $(\boldsymbol{\rho g L_V})$ represents the pressure drop resulting from hydrostatic pressure changes (height variation along the exchanger).

2. Materials and methods

The aim of the conducted experimental study was to determine the minimum flow rate required during Clean-in-Place (CIP) cleaning to ensure effective cleaning of the installation and microbiological safety of the product. Knowing the required flow rate and determining the pressure drop are key for proper pump selection in the CIP station. The tests were conducted on a prototype line for pasteurizing liquid egg mass and its individual components (yolk and egg white), using an external CIP station, the schematic diagram of which is shown in Fig. 2. The CIP station consists of two 50-liter tanks for water/acid and alkali, a circulation pump, and a flow-through heater with a thermostat. The tested installation includes a three-section plate heat exchanger (PHE), a pipeline, and a set of measurement sensors. The use of sensors enabled monitoring of the cleaning process by recording key parameters such as pressure, flow rate, and medium temperature at three points of the system: before the PHE, between the middle and right section, and after the last section.

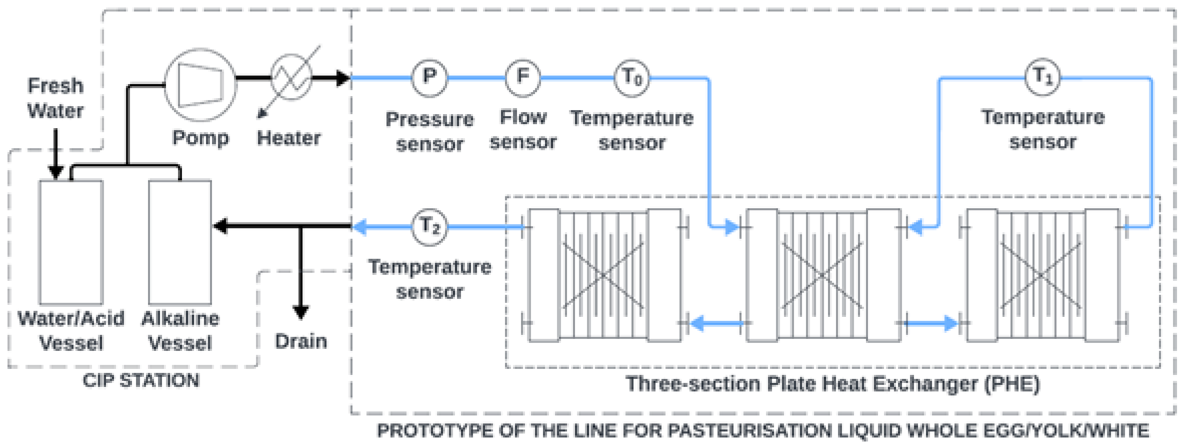

Fig. 2. Schematic diagram of an installation cleaned using the CIP system

A series of cleaning trials was carried out using the CIP station with pumps of different power, providing flow rates in the range of 94–1,554 [L/h]. Due to the design of the test setup, the flow direction during cleaning was consistent with the direction used during pasteurization of whole egg, yolk, and egg white in liquid form. After pasteurization and cooling of the egg mass to a temperature that eliminated the risk of scorching, the installation was cleaned according to an 8-stage sequence detailed in Table 1. Due to the presence of components requiring manual cleaning, two additional stages (II and III) were introduced to rinse the installation of any remaining liquid egg mass, yolk, or egg white before the actual cleaning with aggressive chemicals. This aimed to minimize contamination of the circulating solution with product residues, allowing it to be reused for longer without frequent replacement. During the main cleaning stage (Stage V), a commercial alkaline detergent intended for cleaning piping and equipment in closed systems was used. The detergent concentration was maintained according to the manufacturer's recommendation within the range of 0.8 to 2%, which corresponded to a pH level of 12.81 to 13.21. The detergent operation time was measured from the moment the required temperature (75°C) was reached at the three designated measuring points (Fig. 2).To evaluate the effectiveness of PHE cleaning from egg mass residues, microbiological surface testing of the heat exchanger plates was conducted using commercial Compact Dry plates. After the cleaning cycle, the PHE was disassembled and samples were collected for analysis in accordance with the established procedure.

As part of the research, calculations of pressure drops caused by hydraulic resistance during the flow of water and NaOH solution through the installation during CIP cleaning were performed using Equations Eq. 1 and Eq. 2. Calculations for water were performed over a flow rate range of 50 to 1600 [L/h], increasing in increments of 1 [L/h]. The results were compared with experimental data obtained at various flow rates. The analysis used average measured values of flow rate and pressure drop.

Additionally, for one full CIP cleaning cycle, calculations were performed based on values recorded by the flowmeter, which enabled direct comparison of the calculated results with measured values. The analysis also accounted for the influence of temperature on the physicochemical properties of water and the NaOH solution. The resulting pressure drop values were then compared with those measured during installation cleaning.

Table 1. The specifics of the developed CIP cleaning steps

Stage	CIP program	Function	Cleaning media	Parameters
I	Pre-rinse	to remove residues of egg mass from the installation	fresh water	T ≈ 20[°C]; t = 5 [min]
II	Blowing air through the installation	to remove the remaining water from the installation and a break for manual removal of filter inserts	compressed air	p = 0,4 [MPa]
III	Intermediate rinse	to remove residues of egg mass from the installation	fresh water	T ≈ 20[°C]; t = 5 [min]
IV	Blowing air through the installation	to remove the remaining water from the installation	compressed air	p = 0,4 [MPa].
V	Caustic re-circulation	to dissolve and remove organic micro residues like protein and fats	alkaline detergent (2% NaOH)	T = 75 ÷ 80[°C]; t = 25 [min]
VI	Blowing air through the installation	to recover the remaining caustic from the installation	compressed air	p = 0,4 [MPa]
VII	Final rinse	to flush away chemical residues from the installation	fresh clean water	T ≈ 20[°C]; t = 5 [min]
VIII	Blowing air through the installation	to remove the remaining water and dry the installation	compressed air	p = 0,4 [MPa]

To further analyze the obtained pressure drop values, the Reynolds number for flow through the PHE was also calculated using Equation Eq. 6.

$$Re = \frac{\dot{V} D_e \rho}{N b W_P \eta} \qquad \text{(Eq. 6)}$$

Determining the Reynolds number is a crucial part of flow analysis, as it enables both the assessment of the flow regime and the comparison of results with data available in the literature.

3. Results and discussion

Lower flow rates do not guarantee achieving an appropriate level of microbiological cleanliness. The use of chromogenic plates enabling both qualitative and quantitative assessment allowed the observation that as the flow rate increases, the number of detected microorganisms decreases, and the size and color of the colonies they form also change. In samples a (491 [L/h]) and b (648 [L/h]), microorganisms forming large red colonies predominated, which were effectively removed at higher flow rates. In sample c (996 [L/h]), only small colonies were identified, indicating limited cleaning performance. In contrast, with the use of a pump providing a flow rate of 1,260 [L/h] (sample d), no microorganisms were detected on the surfaces of the PHE plates. Based on this, it can be concluded that in the case of samples a, b, and c, the heat exchanger was not sufficiently flushed of protein residues, which may serve as a substrate for microbial growth. Residual organic matter left in the installation can lead to secondary contamination of the PHE plate surfaces, which emphasizes the importance of proper flow parameter selection in the CIP process.

During the experimental studies, the pressure values and flow rates of the cleaning media varied depending on the cleaning stage, as shown in Fig. 4.

In stage I (pre-rinse), the installation filled with egg mass was initially rinsed with fresh water. Until the complete removal of product residues, increased pressure was observed in the system. In the subsequent rinsing stages, i.e., stage III (intermediate rinse) and stage VII (final rinse), these values changed slightly, remaining in the range of 0.32–0.34 [MPa]. During the circulation of the alkaline cleaning agent (stage V), the pressure ranged from 0.14–0.15 [MPa], indicating stable flow rates. At the same time, the flow rate during the circulation of the alkaline cleaning agent (approximately 790 L/h) was lower than during water rinsing (approximately 1,330 L/h). This difference was due to the fact that during rinsing, fresh water under pressure was constantly supplied to the installation, increasing the pump's efficiency. In contrast, during alkaline cleaning, the flow was generated solely by the operation of the circulation pump. An additional factor contributing to the reduced flow rate was increased hydraulic resistance resulting from the change of medium, and hence its higher density and viscosity.

The flowmeter used recorded large rhythmic fluctuations in flow rate during the tests, which were the result of the pulsating operation of the centrifugal pump used in the CIP station. On the other hand, the measured pressure value remained stable at each stage of the experimental tests, except for the initial spike recorded in stage I.

A comparison of the experimental test results with the theoretical calculations based on the mathematical relationship presented in equation ((Eq. 2), reveals clear local discrepancies (Fig. 4), with a maximum value of δi = 23,1%. Such significant deviations are most likely due to momentary fluctuations in the measured flow rate, which is a key input parameter in pressure drop calculations. It should be emphasized that such fluctuations are difficult to completely eliminate under experimental conditions and can lead to local errors in assessing flow characteristics.

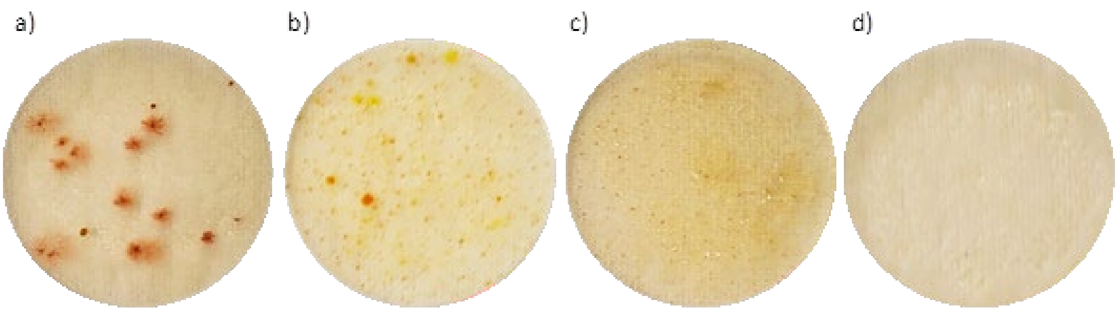

Fig. 3. Microorganisms determined on the surface of PHE plates using Compact Dry chromogenic plates, depending on CIP flow rate. a) 491 [L\h]; b) 648; c) 996; d) 1 260

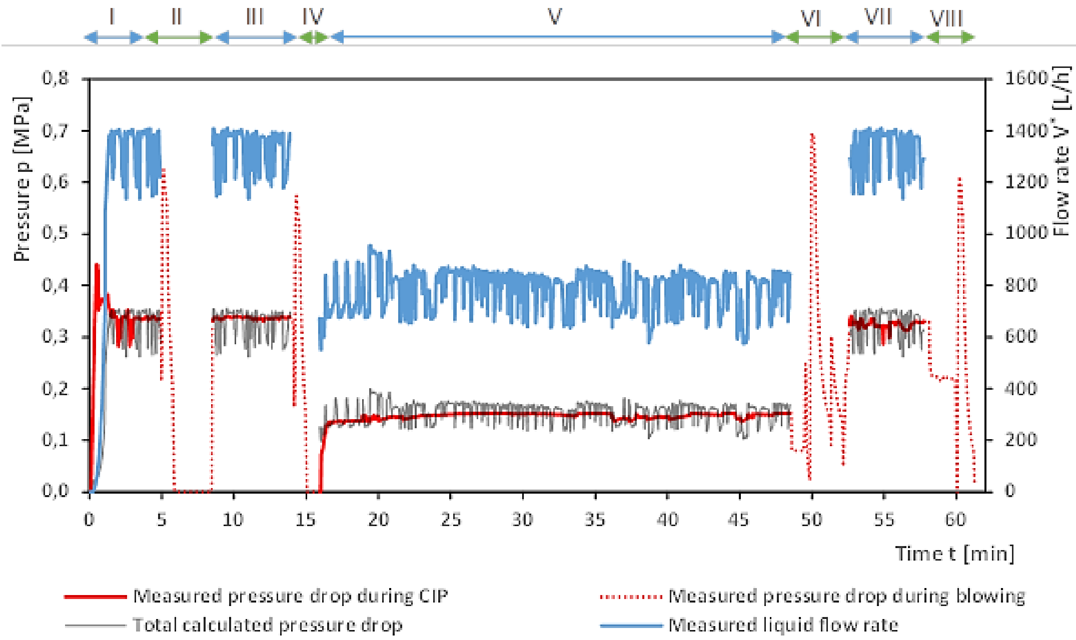

Fig. 4. Comparison of measured and calculated flow parameters during a single CIP cleaning cycle.
I – pre-rinse; II, IV, VI, VIII – blowing air through the installation; III – intermediate rinse;
V – Caustic re-circulation; VII – final rinse

Table 2. Measured and Calculated Pressure Drop

Stage	CIP program	Average measured flow rate	Average measured pressure drop	Calculated pressure drop	Discrepancy
	Symbol	$\dot{V}=\frac{\sum_0^n \dot{V}i}{n}$	$\Delta p_M=\frac{\sum_0^n \Delta p_M i}{n}$	$\Delta p_C=f(\dot{V})$	$\delta=\left\|\frac{\Delta p_C-\Delta p_M}{\Delta p_M}\right\|*100$
	[Unit]	[L\h]	[MPa]	[MPa]	[%]
I	Pre-rinse	1331	0,333	0,326	2,10
III	Intermediate rinse	1329	0,337	0,326	3,26
V	Caustic re-circulation	787	0,146	0,159	8,90
VII	Final rinse	1322	0,324	0,323	0,31

Despite these local deviations, a comparative analysis of the average measured pressure drop values and the values calculated for the corresponding average flow rate indicates much better agreement. The differences between the results range from δ = 0,31% to δ = 8,90% (Table 2), which confirms that using average values allows for much more accurate reflection of actual flow conditions. These results demonstrate the effectiveness of the proposed calculation method and its usefulness in engineering applications, particularly in the analysis of flow through complex systems such as heat exchangers with corrugated channel geometry. The obtained results confirm the correctness of the adopted calculation methodology and its effectiveness in predicting pressure losses in the analyzed system.

At the same time, they highlight the necessity of accounting for flow instabilities in local analyses, especially under conditions of variable hydraulic regimes.

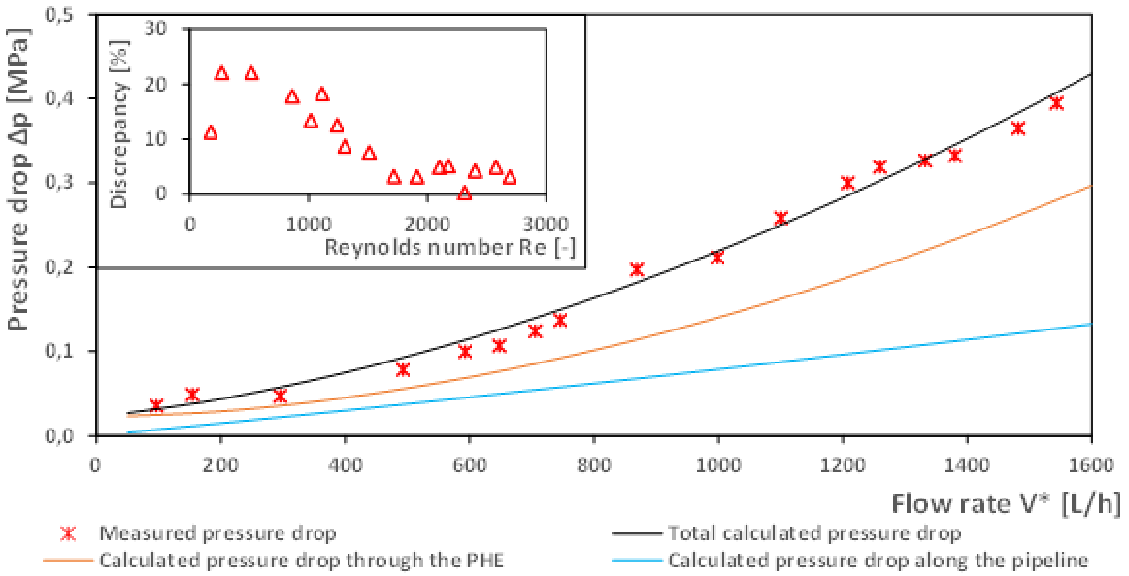

Fig. 5. Comparison of measured and calculated pressure drop through the installation with a three-section PHE during water rinsing

When analyzing the pressure drop calculated and determined experimentally over a wide flow range of 94–1,554 [L/h] (Re = 169–2,768) (Fig. 5), it should be noted that these values are close to each other. Their discrepancy decreases with increasing flow rate. For a flow of 155 [L/h] (Re = 278), the discrepancy is $\delta = 22{,}29$ which is the maximum value recorded during the experiment. However, for flow rates above 743 [L/h] (Re = 1,332), this value drops below 10% (reaching 8.34%), and at a flow of 1,330 [L/h] (Re = 2,386), it is only 0.12%.

The improved accuracy of the mathematical description may result from the fact that increasing the flow rate leads to an increase in turbulence, as expressed by the Reynolds number (Re), which in turn positively affects the predictability of hydraulic resistance. Under turbulent flow conditions, changes in the stream become more stable, and hydraulic resistance is less susceptible to fluctuations. Therefore, at higher flow rates, the mathematical model better reflects the actual conditions in the installation, leading to smaller deviations between the calculated and experimental results. This is a regularity characteristic of flow through a PHE, regardless of the mathematical model used, as described in the literature [13], [21], [23]. The upper limit of transitional flow character in the tested PHE lies between Reynolds number values of Re = 1,200 and Re = 1,500. After exceeding this threshold, a marked improvement in the accuracy of the applied equation is observed.

4. Conclusion

The conducted experimental research aimed to determine the minimum flow rate required during CIP cleaning to ensure effective removal of food residues that serve as a substrate for microbial growth. For the studied installation, which included athree-section plate heat exchanger (PHE), the minimum effective flow rate was 1,200 L/h. The effectiveness of the process was confirmed based on positive results of microbiological analyses performed after the cleaning cycle was completed.

The analysis also considered the impact of flow rate on pressure drop within the system. The experimental results were compared with values calculated using an analytical method, which allowed for an assessment of the accuracy of the applied mathematical model (Eq. 2) in relation to the prototype installation. It was found that the discrepancies between experimental and calculated values decreased with increasing flow turbulence, reaching values below 10% for Re > 1,265, and as little as 0.12% at Re = 2,386.

Based on the conducted analyses, the upper boundary of transitional flow behavior in the tested PHE was also identified, which lies within the Reynolds number range of Re = 1,200 to Re = 1,500. After exceeding these values, the accuracy of the mathematical model significantly increases, indicating a stabilization of hydraulic resistance resulting from a change in flow regime.

The obtained results can be used to optimize cleaning parameters in CIP systems, contributing to increased cleaning efficiency of industrial pasteurization lines, reduced consumption of chemical agents, and improved microbiological safety of the final product.

Nomenclature:

D – pipe internal diameter	[m]	W_p – plate width	[m]
D_e – equivalent diameter of the channel	[m]	b – channel average thickness	[m]
D_P – port diameter of the plate	[m]	f – Fanning factor	[-]
G_c –channel mass velocity	[kg/m^{2}s]	g – gravitational acceleration	[m/s^2]
G_P – port mass velocity	[kg/m^{2}s]	m – coefficient	[-]
K_p – coefficient	[-]	$\dot{m}$ – mass velocity per channel	[kg/s]
L – pipe length	[m]	u – fluid velocity inside channels	[m/s]
L_V – vertical port distance	[m]	Δp – pressure drop	[Pa]
$\dot{M}$ – mass flow rate	[kg/s]	δ – discrepancy	[%]
N – number of channels per pass	[-]	η – viscosity	[Pa s]
P – number of passes	[-]	λ – coefficient of friction	[-]
Re – Reynolds number	[-]	ρ – density	[kg/m^3]
$\dot{V}$ – flow rate	[L/h]		

References

[1] K. Maziarz *et al.*, 'Analysis of Haze Susceptibility in Beers with Unmalted Barley Addition Under Varying Storage Conditions', *Journal of Research and Applications in Agricultural Engineering*, vol. 68, no. 2, Nov. 2023, doi: 10.53502/siwc4991.

[2] J. Diakun, S. Mierzejewska, and J. Przepiórka, 'Monitorowanie parametrów czynnika myjącego w trakcie mycia w przepływie', *Postępy Techniki Przetwórstwa Spożywczego*, vol. 1, pp. 34–36, 2009.

[3] O. Arsenyeva, O. Matsegora, P. Kapustenko, A. Yuzbashyan, and J. Jaromír Klemeš, 'The water fouling development in plate heat exchangers with plates of different corrugations geometry', *Thermal Science and Engineering Progress*, vol. 32, Jul. 2022, doi: 10.1016/j.tsep.2022.101310.

[4] S. Brooks and R. Roy, 'Design and complexity evaluation of a self-cleaning heat exchanger', *Int J Heat Mass Transf*, vol. 191, Aug. 2022, doi: 10.1016/j.ijheatmasstransfer.2022.122725.

[5] C. Spiegel, F. Aselmeyer, W. Augustin, and S. Scholl, 'Quantification method for cleaning-in-place procedures in micro structured equipment', *Food and Bioproducts Processing*, vol. 134, pp. 150–162, Jul. 2022, doi: 10.1016/j.fbp.2022.05.010.

[6] A. L. Bowler, S. Rodgers, D. J. Cook, and N. J. Watson, 'Bayesian and ultrasonic sensor aided multi-objective optimisation for sustainable clean-in-place processes', *Food and Bioproducts Processing*, vol. 141, pp. 23–35, Sep. 2023, doi: 10.1016/j.fbp.2023.06.010.

[7] L. Beckedorff, R. P. P. da Silva, G. S. M. Martins, K. V. de Paiva, J. L. G. Oliveira, and A. A. M. Oliveira, 'Flow maldistribution and heat transfer characteristics in plate and shell heat exchangers', *Int J Heat Mass Transf*, vol. 195, Oct. 2022, doi: 10.1016/j.ijheatmasstransfer.2022.123182.

[8] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, and S. A. Tassou, 'Waste heat recovery technologies and applications', Jun. 01, 2018, *Elsevier Ltd*. doi: 10.1016/j.tsep.2018.04.017.

[9] A. Durmuş, H. Benli, I. Kurtbaş, and H. Gül, 'Investigation of heat transfer and pressure drop in plate heat exchangers having different surface profiles', *Int J Heat Mass Transf*, vol. 52, no. 5–6, pp. 1451–1457, Feb. 2009, doi: 10.1016/j.ijheatmasstransfer.2008.07.052.

[10] P. Kapustenko, J. J. Klemeš, O. Arsenyeva, and L. Tovazhnyanskyy, 'PHE (Plate Heat Exchanger) for Condensing Duties: Recent Advances and Future Prospects', Jan. 01, 2023, *MDPI*. doi: 10.3390/en16010524.

[11] A. Kumar Rai, V. Sachan, O. Mohammed Ismael, and H. Mahdi, 'AN EXPERIMENTAL STUDY OF HEAT TRANSFER IN A PLATE HEAT EXCHANGER', IJARET, 2014. [Online]. Available: www.iaeme.com/ijaret.asp

[12] C. Gulenoglu, F. Akturk, S. Aradag, N. Sezer Uzol, and S. Kakac, 'Experimental comparison of performances of three different plates for gasketed plate heat exchangers', *International Journal of Thermal Sciences*, vol. 75, pp. 249–256, Jan. 2014, doi: 10.1016/j.ijthermalsci.2013.06.012.

[13] M. A. H. Mudhafar, 'Numerical study of two-phase flow in multi-channels plate heat exchanger', *International Communications in Heat and Mass Transfer*, vol. 138, Nov. 2022, doi: 10.1016/j.icheatmasstransfer.2022.106380.

[14] 'https://www.csidesigns.com/blog/articles/how-do-heat-exchangers-work', Sep. 2024.

[15] D. A. . Seiberling, *Clean-in-place for biopharmaceutical processes*. Informa Healthcare, 2008.

[16] Z. Kowalczuk and M. S. Tatara, 'Improved model of isothermal and incompressible fluid flow in pipelines versus the Darcy-Weisbach equation and the issue of friction factor', *J Fluid Mech*, vol. 891, 2020, doi: 10.1017/jfm.2020.131.

[17] Jaćimović. Nikola, M. Stamenić, and P. Kolendić, 'A Novel Method for the Inclusion of Pipe Roughness in the Hazen- Williams Equation', *FME Transactions*, vol. 43, no. 1, pp. 40–46, 2015, doi: 10.5937/fmet1501040S.

[18] T. Hobler, *Inżynieria chemiczna Ruch ciepła i wymienniki*. Warszawa: Państwowe Wydawnictwo Techniczne, 1959.

[19] A. A. Neagu, C. I. Koncsag, A. Barbulescu, and E. Botez, 'Estimation of pressure drop in gasket plate heat exchangers', *Ovidius University Annals of Chemistry*, vol. 27, no. 1, pp. 62–72, Jun. 2016, doi: 10.1515/auoc-2016-0011.

[20] S. Gusew and R. Stuke, 'Pressure Drop in Plate Heat Exchangers for Single-Phase Convection in Turbulent Flow Regime: Experiment and Theory', *International Journal of Chemical Engineering*, vol. 2019, 2019, doi: 10.1155/2019/3693657.

[21] S. Gusew and R. Stuke, 'Pressure Drop in Plate Heat Exchangers for Single-Phase Convection in Turbulent Flow Regime: Experiment and Theory', *International Journal of Chemical Engineering*, vol. 2019, 2019, doi: 10.1155/2019/3693657.

[22] F. A. S. Mota, E. P. Carvalho, and M. A. S. S. Ravagnani, 'Modeling and Design of Plate Heat Exchanger', in *Heat Transfer Studies and Applications*, 2015, pp. 165–199.

[23] S. Mohebbi and F. Veysi, 'Numerical investigation of small plate heat exchangers performance having different surface profiles', *Appl Therm Eng*, vol. 188, Apr. 2021, doi: 10.1016/j.applthermaleng.2021.116616.