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BIOMASS AS AN ALTERNATIVE FUEL – SELECTED ASPECTS

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ABSTRACT

In July 2023, the International Maritime Organization (IMO) revised its strategy for reducing greenhouse gas (GHG) emissions from ships. The changes adopted mean that ships should not emit GHGs as early as 2050, not, as originally assumed in the first version of this strategy, 2100. In turn, on 1 January 2025, a European Union regulation (FuelEU Maritime) on ships entering European Union ports with the aim of supporting the decarbonisation of shipping came into force. In this situation, alternative fuels and all technologies related to the use of renewable energy sources on ships, low-emission fuels and clean technologies are of particular importance because they contribute to the reduction of the consumption of fossil fuels. One of the alternative fuels that meets these criteria is ordinary or torrefied timber pellets. This type of fuel requires the use of special transport installation solutions, such as pneumatic solutions. The article presents selected results of experimental tests conducted using a test stand. On their basis, the hypothesis that the pressure drop in the installation depends on various operating states of the ship and the parameters of the transported material was confirmed.

Keywords: ship's power plant, environment protection, biomass, pneumatic transport

INTRODUCTION

Member states of the International Maritime Organization (IMO) adopted changes to the strategy for reducing greenhouse gas (GHG) emissions from ships during the meeting of the Marine Environment Protection Committee (MEPC 80) in July 2023. The new goal that was set is to achieve the total reduction of these gases in 2050 (50 years earlier than assumed in the first version of the strategy from 2018). To facilitate the achievement of this goal, the IMO has introduced certain checkpoints for the reduction of GHG emissions from ships. Thus, by 2030, emissions should be reduced by 20%, striving for 30%, and by 2040 they should be reduced by 70%, striving for 80%, compared to 2008. The IMO 2023 Strategy is therefore a framework for member states, defining the level of ambition for reducing GHG emissions in international shipping. In particular, it envisages a reduction of the carbon intensity of international shipping (reduction of CO_2 emissions per unit of transport work) by an average of at least 40% by 2030. The IMO also announced the introduction of the necessary regulatory changes to Annex VI of the MARPOL Convention, which are to be adopted in autumn 2025 and will come into force around mid-2027 [1].

In turn, on 1 January 2025, a European Union regulation known as FuelEU Maritime came into force, concerning ships of all flags with a gross tonnage exceeding 5,000 GT entering ports under the jurisdiction of a European Union (EU) Member State, supporting decarbonisation in international shipping. In the regulation, 'greenhouse gas emissions' were defined as the release of carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O) into the atmosphere. The regulation is intended to ensure an initial 2%

reduction in GHG emissions in the years 2025 to 2029 compared to the average greenhouse gas emission intensity in 2020. The further target is to reduce this value to 6% in the years 2030 to 2034, accelerating further starting in 2035 to finally achieve an 80% reduction by 2050. FuelEU Maritime also introduces, from 1 January 2030, an obligation for passenger ships and container ships moored at a quay to use shore-power or alternative zero-emission technologies, e.g. fuel cells, in ports covered by Article 9 of the Regulation of the European Parliament and of the EU Council from 13 September 2023 on the development of alternative fuel infrastructure [2, 3]. It is worth emphasising that these goals not only mean reducing emissions on the ship itself (tank-to-wake) but also include the processes of raw material extraction, fuel production and fuel transportation, storage and bunkering on the ship (well-to-tank). This comprehensive approach, called 'well-to-wake', concerns the reduction of GHG emissions throughout the entire fuel life cycle [2].

When it comes to improving the energy conversion process on the ship itself, continuously reducing and finally eliminating the combustion of fossil fuels on the ship plays a fundamental role in this. One possibility is to use fuels produced from biomass, i.e. according to the regulation, biofuels or biogas. On the path to full decarbonisation, solutions involving the combustion of mixtures of petroleum-derived fuels with biofuels should be treated as transitional. For example, Zastempowski et al. [4] found that the use of bioethanol as an additive to gasoline in a small spark-ignition outboard engine reduced CO emissions by 67% and hydrocarbons (HC) emissions by 56%. However, changes were noticeable only when the bioethanol content in the fuel exceeded 30%. In turn, Wei et al. [5] examined the effect of heavy fuel oil and biodiesel mixtures on engine combustion and black carbon emissions in a two-stroke low-speed engine. It was found that as the share of biodiesel increased, the degree of carbonisation of soot particles in the exhaust gases became lower than in the oxidation process, which resulted in a decrease in the degree of graphitisation.

'Biofuels' are defined according to Article 2, second paragraph, point 33 of Directive (EU) 2018/2001 [6], i.e. only liquid fuels for transport produced from biomass [3]. The FuelEU Maritime Directive omits solid fuels produced from biomass, despite the fact that according to the definition in the second paragraph, point 27 of Directive (EU) 2018/2001, 'biomass fuels' refers to gaseous and also solid fuels produced from biomass. It is also worth emphasising that the FuelEU Maritime regulation allows the use of only certified sustainable fuels. This means that when biofuel or biogas is produced from food and feed crops, it is considered to have the same emission factor as the least favourable fossil fuel path. The FuelEU Maritime Directive is scheduled to be revised by 31 December 2027, which may extend its scope and may also take into account any IMO requirements adopted by that time [2]. It is possible that solid fuel produced from biomass, such as pellets, will also be allowed in EU ports to reduce GHG emissions, especially due to biofuel and biogas shortages and their high prices.

Some biofuel suppliers point out that stringent biofuel sustainability standards have a significant impact on the amount of fuel available that qualifies for use in transport [7]. Therefore, in Japan, which practically does not have to comply with EU directives, three companies – NYK Line, NYK Bulk & Projects Carriers and Tsuneishi Shipbuilding Co., Ltd. – are planning to build a ship powered by wood pellets, which are classified as 'biomass'; this is also true in the US and Canada. From these countries, pellets would be transported as cargo on ships to Japan [8].

Regardless of the solution to the engine room itself, problems arise related to the operation of pellet transport from the storage tank to the engine room. This article presents selected results of experimental tests conducted using a test stand, the main purpose of which was to verify the hypothesis that the flow resistance in the transport installation depends on its various configurations and the various operating states of the ship. Research in the literature on this issue did not give satisfactory results, which directly contributed to the decision to carry out experimental research.

PELLETS AS MARINE FUEL

Solid biomass in an unprocessed form, such as sawdust or wood chips, is characterised by a lower bulk density and lower calorific value than coal, which was commonly used as ship fuel at the beginning of the 20th century. This means that the volume of fuel reserves needed to achieve the same energy effects will be larger, which limits the valuable cargo capacity of the ship. Subjecting biomass to the process of refinement through mechanical compaction brings it closer to coal in terms of the bulk density and calorific value. Biomass refined in this way is most often used in the form of briquettes or wood pellets.

Another, more effective process for biomass refinement is torrefaction. It involves heating biomass, usually at a temperature of 200 to 300 °C, in an atmosphere of inert gases, to obtain a material with properties very similar to coal, so-called bio-coal. So-called second-generation pellets can also be produced from torrefaction biomass. Typical torrefaction increases the energy density of the biomass by about 30% [9].

Table 1 shows the calorific values and bulk densities of ordinary and torrefied timber pellets and, for comparison, coal and conventional marine fuels, as well as alternative fuels such as liquefied natural gas (LNG) and methanol. The volume of fuel reserves for the assumed range of the ship depends on these two parameters.

Tab. 1. Selected properties of pellets, coal, marine diesel oil (MDO), heavy fuel oil (HFO) and alternative fuels [10]

Fuel	Calorific value [MJ/kg]	Mass density [kg/m^3]
Ordinary timber pellet	19.5	630–750 [1)]
Torrefied pellets	23–26	750–850 [1)]
LNG	49	431–464 [2)]
Methanol	20	794 (at temp. 15 °C)
Marine diesel oil (DMA)	40	890 (at temp. 15 °C)
Heavy fuel oil (RMK 700)	39.4	1010 (at temp. 15 °C)
Hard coal	16–29	800–1000 [1)]
		[1)] dump density [2)] at boiling point

According to the data presented in the table, these parameters practically coincide for hard coal and torrefied pellets. The stock of regular pellets would have only a slightly larger volume than coal or methanol.

PELLET-POWERED SHIP POWER PLANT SOLUTIONS

The specificity of the energy source on board, which is pellets, basically imposes two basic solutions for the power plant. The first is an adaptation of the last coal-fired power plant designs from the end of the 20th century [11, 12]. The characteristic feature of these designs was the use of environmentally friendly fluidised bed boilers and high-efficiency steam power plant cycles. Thanks to this, it was possible to reduce the NO_x and SO_x emissions generated during coal combustion. This adaptation of the power plant, where pellets were proposed as fuel for boilers, was described in detail in [10]. This was a case study in which the research object was a ro-pax ferry, intended to operate on the Baltic Sea.

The authors placed particular emphasis on safety aspects related to the use of pellets as fuel. Selected original results of tests of the heat transfer coefficient in the fluidised layer conducted on a physical model of a fluidised boiler subjected to simulated ship rolling were also presented. The work was concluded with the results of steam cycle and fuel reserve calculations, assuming that a simple steam cycle is implemented in the engine room. A simplified schematic diagram of this solution is shown in Fig. 1.

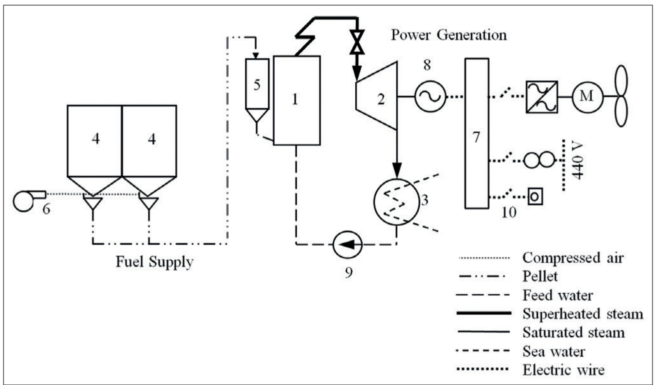

Fig. 1. Simplified schematic diagram of a pellet-powered steam power plant
1 – fluidised bed boiler; 2 – steam turbine; 3 – condenser; 4 – storage of pellets; 5 – daily hold of pellets; 6 – air compressor; 7 – main switchboard; 8 – generator; 9 – water supply pump; 10 – shore connector

The second power plant solution proposed by the Japanese NYK Line, NYK Bulk & Projects Carriers and Tsuneishi Shipbuilding Co., Ltd. also involves the thermal conversion of biomass, but not through combustion; instead, it occurs through gasification in a gasifier installed directly on the ship [8]. As a result of a controlled thermochemical reaction called gasification, biomass (in this case, e.g. wood pellets) is decomposed into a flammable gas that is a mixture of carbon monoxide, hydrogen and methane, as well as coal, carbon dioxide and water.

The proportions of the individual components depend on the temperature, pressure and humidity of the biomass [13]. After processing, flammable gases are fed to the engine driving the generator. The concept of a biomass gasifier power plant is shown in Fig. 2. If the basic cargo carried by a ship with such a power plant consists of pellets, as in the case of the Japanese project, then a solution known as 'cargo to fuel' can be implemented. This means that the cargo tank serves as a fuel storage tank, as, for example, on ships transporting liquefied petroleum gas (LPG) [14, 15]. Using cargo as a fuel source allows shipowners or charterers to achieve significant cost savings by, among other things, reducing the time and fees for bunkering.

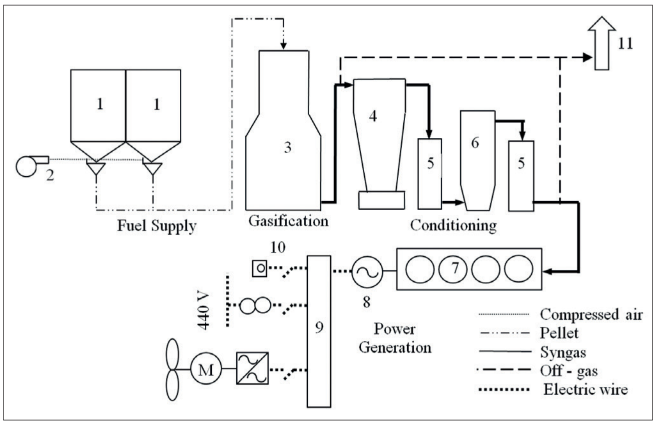

Fig. 2. System diagram of a pellet-powered gas engine power plant
1 – storage of pellets; 2 – air compressor; 3 – gasifier; 4 – cyclone; 5 – cooler; 6 – filter; 7 – gas engine; 8 – generator; 9 – main switchboard; 10 – shore connector; 11 – flare

The sensitivity of the fluidised layer to ship rolling, demonstrated in [10] and resulting in a decrease in boiler output, became an additional reason to analyse the fuel transport system from this perspective. The reason for the decrease in boiler output was characteristic cyclical changes in the value of the heat transfer coefficient from the fluidised layer, adequate to the period of swinging motion [16].

DESCRIPTION OF THE RESEARCH STAND

The research stand made it possible to test the flow resistance (Δp) of various granular materials at varying flow rates ($\dot{m}$), lateral swing periods (T) and lengths and configurations of the transport pipeline (K). The pipelines, assembled in various configurations, were made of a transparent material that allowed the transport process to be observed. The model of the installation was placed on a movable platform, as shown in the diagram of the stand presented in Fig. 3. The platform could be tilted in both directions with a maximum angle of 30o.

The granular material used consisted of wheat grain (762 kg/m^3), rice (740 kg/m^3) and groats (652 kg/m^3). The bulk density of each material is given in parentheses. The concentration of granular material in the stream of transporting air was regulated by means of a valve (5) placed under the lower material tank. Changing the valve opening angle (β) made it possible to change the mass flow ($\dot{m}$). The mass flow value was determined based on the measurement of the transport time of a specific portion of granular material between the tanks. The blower, with a maximum capacity of 350 m^3/h, was powered by an electric motor with an adjusTable number of revolutions, which in turn made it possible to change the speed of the transporting air. The smooth adjustment of the actuator piston rod feed speed made it possible to change the platform oscillation period (various rolling periods of a ship). A hot-wire anemometer with a measuring range of 0.2 to 17 m/s and a measurement resolution of 0.1 m/s was used to measure the air speed and temperature. The flow resistance was determined using a differential manometer with a measurement range of -15 to +15 kPa and a resolution of 1 Pa. Measurement data from the devices were saved on the hard disc of a laptop computer and then processed in Microsoft Office Excel.

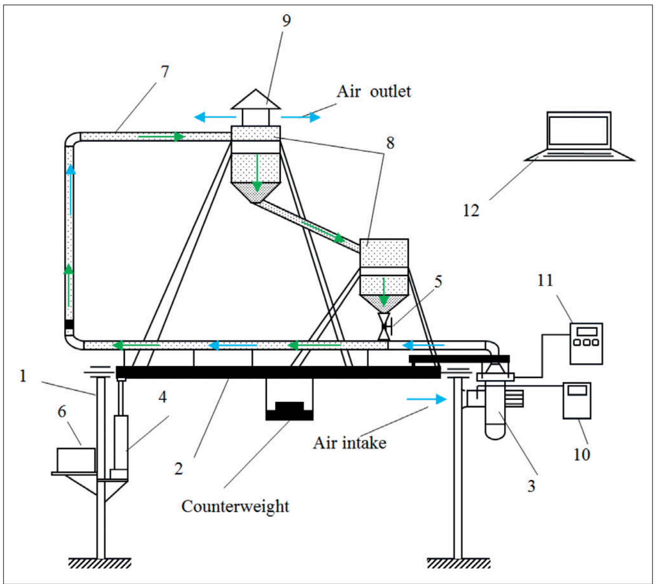

Fig. 3. Research stand for solid fuel pneumatic transportation
1 – platform base; 2 – movable platform; 3 – radial air blower;
4 – electric screw actuator; 5 – capacity control valve; 6 – electric power supply;
7 – transport pipes of variable geometry and length; 8 – tank;
9 – cyclone air outlet; 10 – thermo-anemometer;
11 – differential pressure gauge; 12 – laptop computer

SELECTED RESEARCH RESULTS

To obtain a full picture of the phenomenon, the research was divided into several stages. The first two stages concerned research carried out with a stationary platform (no ship rolling or a fixed lateral tilt with an angle (α) occurred). In the second stage, research was carried out with the platform set in an oscillating motion with different periods. In the third stage, selected measurements from the first and second stages were repeated, but for different configurations of the pipeline installation and with the use of different granular materials. Previously obtained research results [17, 18] provided justification for conducting further work in this area.

A representative example from the first stage of the research consists of the results presented in Fig. 4. They indicate the differences in the resistance characteristics for the same material (wheat grain) for two platform positions, i.e. the horizontal position ($\alpha = 0°$) and with a fixed lateral tilt ($\alpha = 30°$).

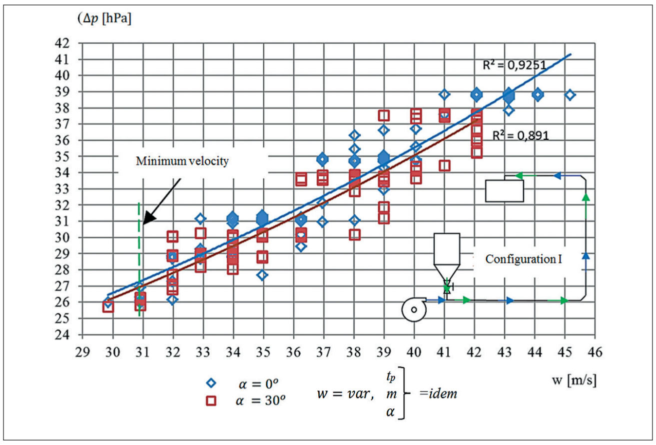

Fig. 4. Flow resistance in pipeline (configuration I) during transport of wheat at tilt angles α = 0° and α = 30°

The flow characteristics also show the minimum air velocity (w), below which the saltation phenomenon occurred. The course of the characteristics indicates a difference in flow resistance for these two platform positions. The resistance is lower at a fixed lateral tilt. This results from the lower geometric height to which the material is transported. Similar relationships were obtained for the remaining materials, with the largest quantitative changes occurring for the material with the highest density [17].

Fig. 5 shows the course of resistance changes depending on the platform inclination angle at a constant flow rate ($\dot{m}$) for the same pipeline configuration for all three materials. The measurements were performed for three inclination angles.

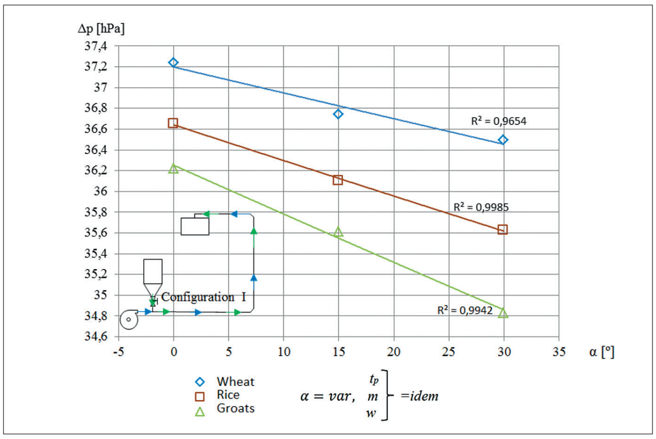

Fig. 5. Pressure drop in pipeline (configuration I) in relation to the platform inclination angle for various materials

The analysis of the results of this experiment indicates that the differences in pressure drops for different platform inclination angles are linear. The largest quantitative pressure drop occurs for the material with the highest density, i.e. wheat grains. The reduction in flow resistance for larger inclination angles results, as previously presented, from the decrease in the geometric lifting height. Qualitatively similar changes were obtained for other pipeline configurations. The pressure drops themselves were larger for configurations with longer pipelines or with a greater number of piping bends.

In the second stage of the tests, the platform was given an oscillating motion. Two characteristic cases are presented as representative results from this stage. The first one shows the flow resistance in the installation at a constant period of oscillation and with a variable material mass flow (Fig. 6). The second case describes the dependence of flow resistance in the installation on the swinging period at a constant material mass flow (Fig. 7).

The graphs presented in Fig. 6 indicate that the nature of the changes is the same for each tested material. It should be added that the velocity of the transporting air was constant, while the amount of the dosed material was increased by gradually increasing the opening angle of the control valve (5). The swinging movement of the platform took place with a constant period of 45 s and with an amplitude of 30°.

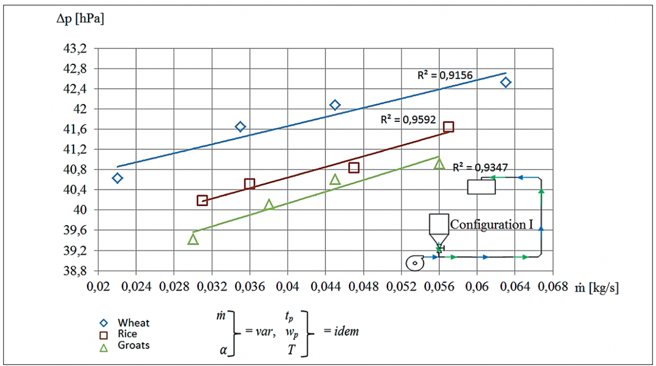

Fig. 6. Pressure drop in pipeline (configuration I) as a function of the material mass flow rate for three different granular materials with a constant platform swinging period

The increase in the concentration of solid material leads to greater pressure drops. In addition, the flow resistance is greater for the material with a higher density. The average pressure drop during the movement of the platform is greater than in the fixed position; it is influenced by the inertia of the grains and the observed effects of material being thrown onto the walls during transport.

This is confirmed by the second studied case, i.e. the study of the pressure drop as a function of the swinging period. In this case, the studies were conducted with a constant material concentration but a variable period. Typical periods of ship lateral rolling range from about 8 s for small units to about 20–30 s for large units. Due to the safety of the stand structure, the permissible periods of platform swinging had to be no less than approximately 40 s. The period was therefore changed in the range of 45 to 105 s, which was sufficient to determine the nature of changes in the flow resistance as a function of the period. As can be seen in Fig. 7, changes in the rolling period affect the flow resistance. With an increasing rolling period, the resistance decreases, and it reaches its lowest value after the platform stops. Similarly to the other cases, the changes are greater for the material with a higher bulk density. Moreover, for shorter swinging periods, greater pressure drops result from more intensive material throwing during transport, while smaller pressure drops occur for the slow movement of the platform with long swinging periods.

To illustrate the research from the third stage, Figs. 8 and 9 show measurement results like those shown in the example in Fig. 7, but for two other configurations of the transport installation.

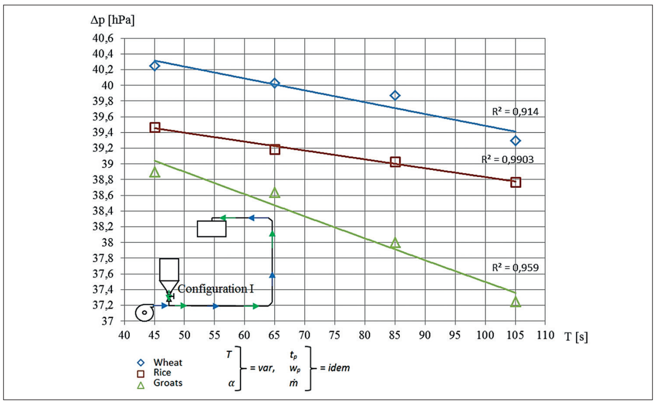

Fig. 7. Pressure drop in pipeline (configuration I) as a function of platform swing period for three different granular materials

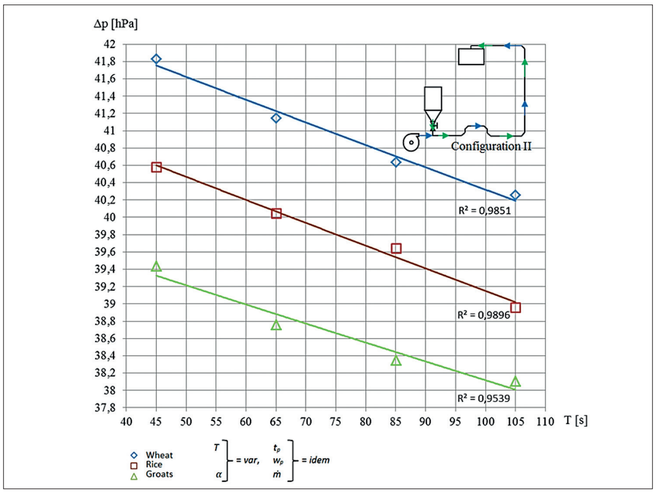

Fig. 8. Pressure drop in pipeline (configuration II) as a function of platform swing period for three different granular materials

Additionally, four pipe bends (90°) were introduced in the horizontal section (configuration II), and in configuration III, compared to configuration I, four bends were introduced in the vertical section. The total length of the pipeline also changed slightly, i.e. from 5.74 m for configuration I to 6.15 m for configuration II and 6.55 m for configuration III. In total, tests were carried out on four installation configurations. A greater length of the pipeline and more elements increasing the local resistance (pipe bends) generally result in increased flow resistance. In particular, noticeable changes in the flow structure were observed for configuration III in the vertical section, which also resulted in the highest flow resistance, also caused by a slightly greater pipeline length. It is advisable to use the smallest possible number of pipe bends in the vertical sections of the installation.

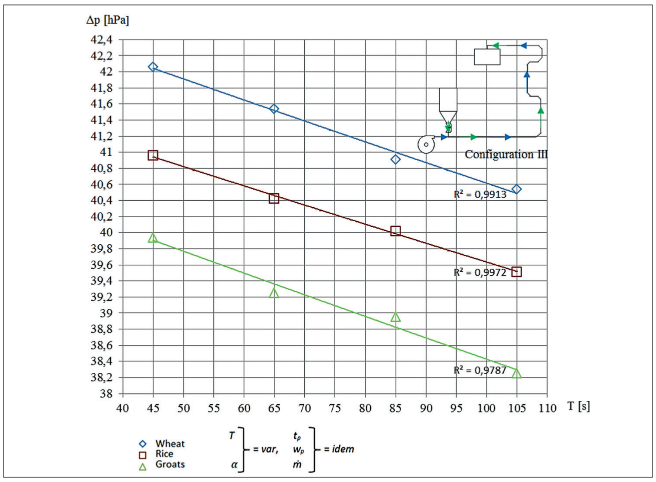

Fig. 9. Pressure drop in pipeline (configuration III) as a function of platform swing period for three different granular materials

SUMMARY

The conducted research allowed a better understanding of the problems of the pneumatic transport of solid fuel in marine conditions. Granular material in the form of plant seeds was used for the laboratory tests, which reproduced well the properties of pellets, considered as the recommended alternative fuel.

The results of the experimental tests confirmed the hypothesis that the flow resistance in the transport system depends on its different configurations and the different operating conditions of the ship. However, the changes in the resistance values are insignificant in the case of small changes in the period of the simulated ship rolling. Greater pressure drops occur for shorter periods of ship rolling.

Changes in the mass concentration of granular material or its bulk density had a more significant effect on changes in flow resistance, because this was associated with an increase in the transport load at the same air flow rate. The geometric lifting height, the pipeline length (linear resistance) and the sum of local resistances have a significant impact on the resistance value. For this reason, in order to minimise the air compressor's power, it is recommended to place the solid fuel tank as close to the engine room as possible, e.g. in front of the superstructure. The height of the installation should also be minimised.

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