energies

Article

Design and Experimental Tests of a Four-Way Valve with the Determination of Flow Characteristics for Building Central Heating Installations Using Solid Modeling

Mariusz Niekurzak * and Jerzy Mikulik

Faculty of Management, AGH University of Krakow, 30-067 Krakow, Poland; mikulik@agh.edu.pl
* Correspondence: niekurz@agh.edu.pl

Abstract: The article presents the design of a four-way valve, implemented in SolidWorks software (SOLIDWORKS® i 3DEXPERIENCE® Works Simulation) and used for central heating installations in buildings. The project was carried out in order to examine the innovative design of the medium mixing mechanism and to conduct strength and FMEA analysis. The innovative solutions proposed by the authors in this work will allow valves of this type to meet stringent environmental standards. These standards are currently being introduced for this type of structural element of machine parts as part of the energy transformation of buildings. Potential failures occurring in individual elements of the four-way valve were also tested using Failure mode and effects analysis. In addition, strength tests were performed in SolidWorks software using static analysis, and optimization tests were performed on the refrigerant in terms of its impact on the environment. The characteristics of the tested materials in the valve design show that the best materials are brass and stainless steel. Brass has a Poisson's ratio of 0.33, a tensile strength of 478.4 MPa and a yield strength of 239.7 MPa. In turn, stainless steel is characterized by the following parameters: Poisson's ratio of 0.27, tensile strength of 685 MPa and yield strength of 292 MPa. The designed valve reduces energy consumption by 30% through a properly designed medium flow with the appropriate selection of materials. Moreover, the design reduces the thickness of the contaminant layer by 0.17 mm, with a capacity factor of −2.50% and an evaporator Δp of 3.10% (53 kPa). The performed research provides knowledge on the subject selection of appropriate material, a description of the potential failures of the structural elements of the designed four-way valve and methods of counteracting these failures. The article presents the optimization role of the tested component in the context of sustainable development.

Keywords: four-way valve; mixing valve; heating; cooling; optimization of working medium flow; sustainable development; assembly design in SolidWorks software

check for updates

Citation: Niekurzak, M.; Mikulik, J. Design and Experimental Tests of a Four-Way Valve with the Determination of Flow Characteristics for Building Central Heating Installations Using Solid Modeling. *Energies* **2024**, *17*, 2152. https://doi.org/10.3390/en17092152

Academic Editors: Anatoliy Pavlenko and Hanna Koshlak

Received: 25 March 2024
Revised: 28 April 2024
Accepted: 29 April 2024
Published: 30 April 2024

1. Introduction

Currently, energy management is focused on sustainable development and savings, a focus which is present in solutions that are presented for problems in the cooling/heating industry and that are used in various fields, such as the food industry, energy, HVAC, automotive, etc. An element that plays a key role in a cooling/heating system is the four-way valve. Its role is to maintain the direction of compressor operation regardless of the selected cooling or heating mode. During the heating mode, the compressor's task is to pump the refrigerant into the exchanger of the cooling/heating system, in which the condensation process takes place, i.e., where heat is released. In the cooling mode, the direction of the process described above is reversed, so the condenser device in the heating mode functions as an evaporator, which means that the heat is supplied to the lower source, which is the external environment [1]. The heating/cooling mode is changed using a four-way valve, which changes the flow direction thanks to a mechanism (slipper) mounted at the intersection of the cooling/heating system. Thanks to the appropriate valve design, smooth flow regulation is possible, which is important for sustainable development. A properly designed structure is responsible for the following:

- Precise control of the flow of the refrigerant introduced into the system, which allows for adaptation to the current environment and operating conditions of the cooling/heating system;
- Reduction of greenhouse gas emissions through the increased efficiency that results from the minimization of the amount of flow of the factor required at a given moment;
- Durability of the system, of which the four-way valve is a part. Lower consumption resulting from optimal refrigerant flow results in reduced use of the cooling/heating system devices.

Taking these comments into account, the work aims to design innovative design changes to the four-way valve using solid modelling. The innovative solutions proposed in the work by the authors will allow valves of this type to determine the optimal flow characteristics of the medium, taking into account strength parameters and meeting stringent environmental standards. These standards are currently being introduced for this type of device as part of the energy transformation of buildings.

The four-way valve is an important component in optimizing medium flow and increasing energy efficiency in the context of sustainable development. Therefore, the valve's energy efficiency and emissivity depend on the correct design of valve components and technical and technological solutions.

Our detailed work goals include the following:

- Assembly design of a four-way valve in SolidWorks software. The goal here is detailed technical documentation of the created assembly geometry, including isometric projections, dimensions, operations used, types of threading (parameters), units used, relationships between sketch elements of each stage of solid creation, and instructions for the activities performed in the SolidWorks software in the form of photographs. The entire project is made of two separately created parts: a four-way valve body and a replaceable lever.
- Examination of potential failures of individual elements of the four-way valve using failure mode and effects analysis.
- Strength tests in SolidWorks software using static analysis.
- An analysis of refrigerant optimization in terms of environmental impact.

Autodesk® CFD software(SOLIDWORKS® i 3DEXPERIENCE® Works Simulation) creates computer simulations of fluid dynamics. CFD stands for computational fluid dynamics, which utilizes a numerical method in order to solve and analyze problems related to fluid flows. Computational fluid dynamics is a type of computer simulation that can be used to predict the behaviors of various factors. The software enables simulations in 2D, 3D and axisymmetric 2D and can be used to mesh the model in an unstructured manner, both at the inlet, outlet, and bends, ensuring mesh quality within a computationally acceptable range, and ensuring that the mesh quality meets computational accuracy requirements [1,2]. The model also calculates the time evolution of solutions to discrete or continuous equations for transport properties related to pressure, velocity vectors, and temperature distribution in free space or around solid objects. CFD analysis can be performed on physical models or simulations. The final result is a simulation of the way that a given factor flows through the designed object.

The article is organized as follows. Section 2 contains a detailed description of the research approach based on the latest literature on the subject. Section 3 describes the research methodology used. Section 4 presents the experimental results and their interpretations. Section 5 contains the conclusions of the research, indicating its limitations, practical application and future directions of research in this field.

2. Literature Review

A four-way valve, also known as a 4d mixing valve, is a device used in heating, refrigeration, ventilation and air conditioning systems to regulate the flow of liquids or gases and to control temperature. Commonly used in central heating installations. This type of valve has four ports, or inputs/outputs, which allows for the control of two streams of substances and for them to be mixed according to set proportions [3–5]. The use of four-way valves is particularly important in the case of heating, cooling and air-conditioning systems, where precise control of temperature and fluid flow is crucial to achieving optimal efficiency and user comfort. These advanced valves not only enable precise mixing of liquids but also direct them to different areas of the system, which allows for effective temperature control in different zones of the building or installation. This works on the principle of opening and closing the appropriate flows, which in turn allows one to adjust the temperature or other system parameters. The four-way valve works as follows [6–9]:

1. Ports and flows: A four-way valve has four ports or inputs/outputs, which are often called "A", "B", "AB", and "OB". "A" and "B" are connection ports for two substance streams (e.g., cooling liquid and return liquid in the heating system). "AB" and "OB" are the mixing and splitting ports.
2. Mixing and separating: The main function of the valve is to regulate the flow of substances through the "AB" and "OB" ports. If the valve is set to "mix," the substances flowing through ports "A" and "B" are mixed in the proportions specified by the valve setting. When set to "split", substances flowing through port "AB" are distributed to ports "A" and "B" depending on the ratio set by the valve.
3. Setting the proportion: The four-way valve has a mechanism that allows one to adjust the flow proportion between the ports. This allows one to adjust the temperature or other system parameters as needed. This is often accomplished through a rotation lever or crank on the valve.
4. Temperature control: In heating and cooling systems, a four-way valve can control the temperature of the liquid circulating in the installation. By changing the proportions between hot and cold liquid, the desired temperature in the circuit can be achieved.
5. Automation: In advanced systems, four-way valves can be controlled automatically by building management systems or controllers. This allows the system to dynamically adjust flow proportions in response to changing external or internal conditions.

The most important elements of the four-way valve design (Figure 1) are [10–13]:

- Valve body: This is the main element of the entire structure, constituting most of its volume. The body has channels with holes through which the media introduced into the system flows. This part of the structure is made of corrosion-resistant metal, the most commonly used are stainless steel and aluminum.
- Container: This is the movable part of the valve, which allows the medium to flow in a controlled manner thanks to two plugged channels that enable the mixing of the medium and its flow in the selected direction.
- Sealing kit: This is a set of all of the elements that seal the valve structure. They are located at the junction of the moving elements with the valve body, blocking uncontrolled leakage of the medium outside the system in which the four-way valve is located.
- Indicator: Usually mounted on the valve lever, this is built in the form of a round element with a transparent cover glass pane enabling the reading of parameters.
- Lever: The second movable part of the structure controls the valve shutter in the direction selected by the user. The lever is most often constructed in the form of a handle or a round control knob. The element has a description of functions depending on the direction of rotation of the lever.

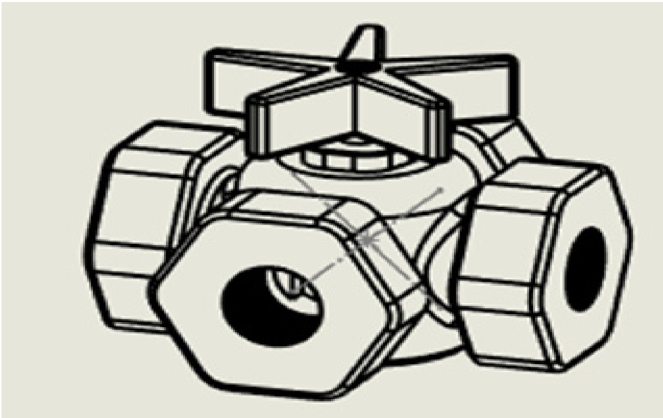

Figure 1. Construction diagram of a four-way valve. Source: own study.

The operating mechanism of the four-way valve is based on the connection of two flow channels. In the center of the connection, there is a valve in the form of a rectangular spacer with rounded corners, which is connected to a lever/regulator by which the flow of the substance (gas or liquid) introduced into the system is manipulated [14]. The connections of the two flow channels with the installation are divided into output and input. In the heating system, the output connections are connected from the boiler to the heat source and back, while the output connections direct the introduced medium, either in the form of a liquid or gas, to the heating system and back to the heat source. The functions resulting from the valve design constitute the overall operating mechanism of the four-way valve, whose main task is to manipulate the factor introduced into the system. These functions are [15–18]:

- Regulation of the direction of medium flow.
- Medium temperature.
- Mixing the medium.
- Limit the reverse flow of the medium.

These functions are possible thanks to the rotation of the four-way valve, which, depending on its position, changes the direction of flow, its intensity and the degree to which the medium introduced into the system is mixed. The designs of the valve positions that change the flow of the medium are shown in Figure 2.

The possibility of regulation involves controlling the flow parameters, which allows the system to be optimized in terms of factor consumption, which in turn translates into savings and reduced machine wear. Depending on the system it is a part of, the four-way valve regulates the temperature of a liquid medium (e.g., water) in a central heating system using radiators. In the air conditioning system, it regulates the direction of flow of gaseous refrigerant [19–24]. The operation of the four-way valve can be automated thanks to an actuator that optimizes heat consumption. Four-way valves are also used in boiler systems with hot water (DHW) tanks. Thanks to the possibility of regulating the flow of the medium, a household user in Poland in the winter can save some energy by setting the valve disc in such a way that half of the heated water flows towards the installation and the other half feeds the tank. Please note that one must properly set the valve, which should be connected to the system so that the circulation pump is located on the side of the installation's power source or the side of the channel from which the medium returns from the installation to the four-way valve. This is also the only possible location of this element in the system described above. The use of a four-way valve translates into the following [25–28]:

- Temperature optimization—parameter adjustment allows one to adjust the temperature in such a way that energy consumption is lower.
- Boiler safety—regulation function protects system elements against too low or too high a temperature, protecting against corrosion or condensation.

- Improved efficiency—maintains the temperature at a specific temperature, stabilizing the refrigerant flow, and improving the effective process of refrigerant flow and energy use in the system.
- Improvement of thermal comfort, i.e., satisfaction obtained from the environmental conditions in which one lives—This is the result of the balance between the loss of the environment and the amount of heat produced by the body.

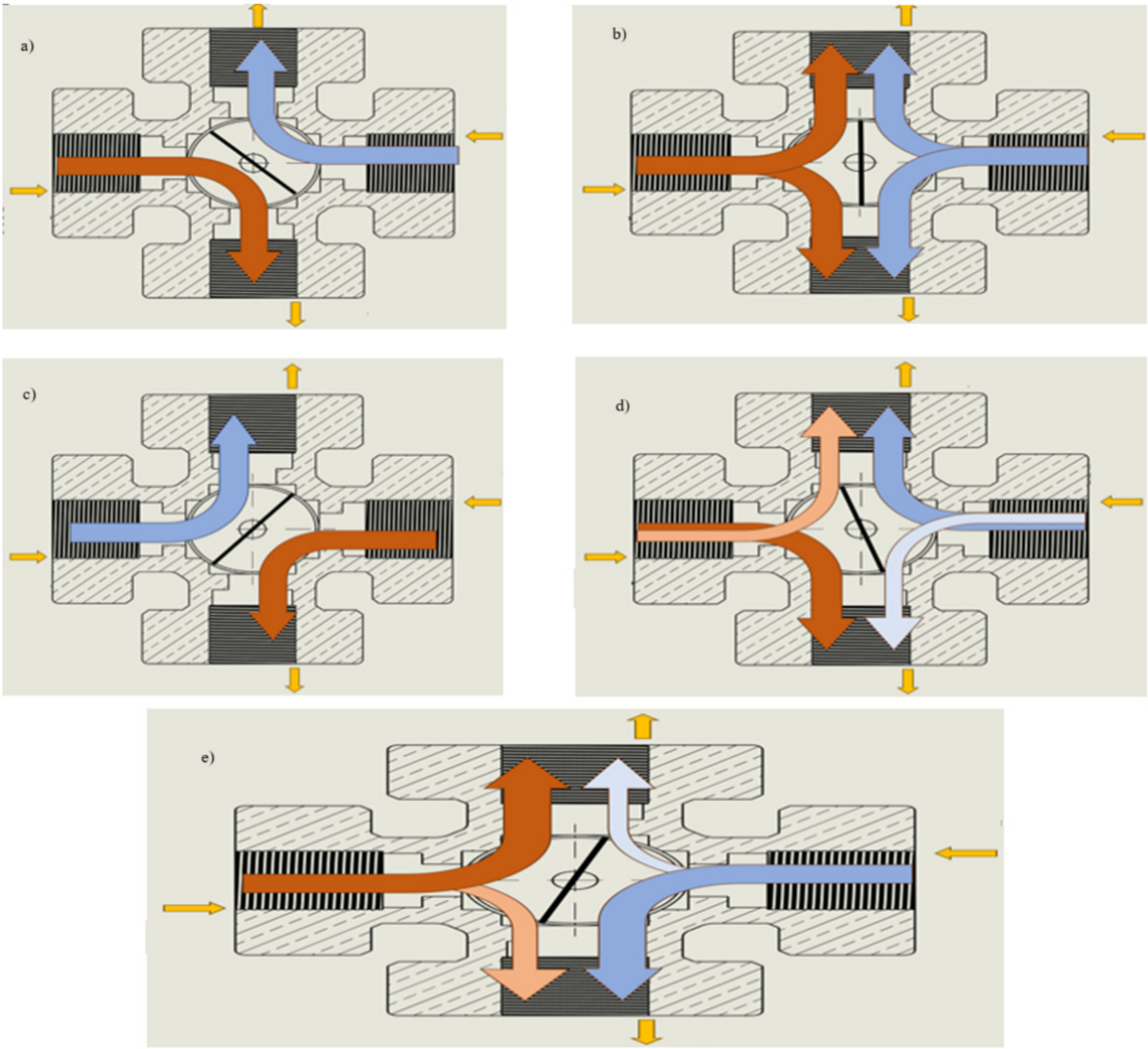

Figure 2. Structures of the mirror position: (**a**) closed flow, (**b**) half-open flow, (**c**) open flow, (**d**) partially open flow 1, and (**e**) partially open flow 2. Source: own study.

The authors in [29] study servo valves, which are important elements of closed-loop electro-hydraulic motion control systems. In their work, they present the principle of their operation and analytical models using computational fluid dynamics analysis. In [30], the authors reviewed the state of the knowledge on directly driven, proportional, and directional hydraulic valves and presented the results of their functionality using the primary characteristics. Using the CFD method, they optimized the spool geometry and modelled the movement for controller design. The authors in [31] presented the advantages of a driven four-way valve using hydraulic control. To improve the control accuracy and adaptability to different operating conditions of impedance control for HDU, a complex control method combining sliding mode control (SMC) and model-based linear extended state observer (MLESO) is used. In [32], a hydraulic valve testing simulator was presented. In the paper, the authors, based on the results of the experimental identification of the friction torque and gravitational torque, combined with the simulation results of time-varying inertia, designed a nonlinear, robust controller based on a disturbance observer with model compensation and a mathematical model basis. In [33], the problems of the hydraulic and thermal imbalances of valves were solved and, based on the computational fluid dynamics method, a 3D model of a pressure-independent control valve with different structures of the control valve core was developed. The selection of different valve core structures can effectively improve the properties of the valve. In [34], the authors look for effective methods by which to reduce or use the flow force of hydraulic valves. In [35,36], the authors present the results of research on improving the efficiency of valves in terms of on/off switching. Ref. [37] presents results regarding the impact of hydrodynamic processes on the characteristics of liquid flow after installing angle fittings in pipeline installations. The analysis was performed based on numerical simulations using 3D Reynolds-averaged Navier–Stokes equations. In turn, Refs. [38,39] present the use of two-phase screw flows in mixed transport pipelines with multiple inlet structures. A mechanical screw flow model was developed based on a multi-inlet VOF. The research results show that the presented strategy and optimization design method can effectively simulate the trends in the formation and evolution of gas–liquid screw flows.

Four-way valves are widely used in various industries and in systems for which there is a need to control the flow of substances and regulate temperature or other parameters. Examples of their use include the following:

- Heating, ventilation, and air conditioning (HVAC) systems: In air conditioning and heating systems, four-way valves allow precise control of the air temperature in rooms by mixing warm and cool media. In ventilation systems, they can be used to regulate airflow and temperature inside buildings.
- Heating and cooling systems: In underfloor heating or cooling systems, four-way valves can regulate the temperature of the liquid circulating through the installation, ensuring thermal comfort for users. In heating systems, these valves can control the temperature of the heating liquid, which allows one to adjust the temperature in individual zones of the building.
- Industrial processes: In the chemical industry, four-way valves can be used to mix various chemicals in specific proportions. In industrial cooling systems, these valves enable process temperature control production.
- Water cooling systems: In water cooling systems, four-way valves can regulate the flow of cooling and hot water, which allows one to maintain the optimal temperature in the cooling circuit.
- Sanitary installations: In the hot- and cold-water supply systems of residential or commercial buildings, four-way valves can help maintain a stable water temperature for the needs of users.
- Food industry: In the food industry, four-way valves can be used to mix and control the temperature of ingredients during the food production process.
- Energy: In some energy production systems, four-way valves can help regulate the flow of cooling or heating medium to maintain optimal operating conditions.

These are just a few examples of the applications of four-way valves. Their versatility and their ability to precisely control the flow and mixing of substances make them important components of many systems that require precise regulation of environmental parameters.

The selection of an appropriate four-way valve depends on the specific needs and characteristics of the system in which it will be used. In particular, one should pay attention to the following [40–44]:

1. System understanding: Identify the type of system in which the four-way valve will be used (e.g., HVAC, heating system, chemical industry, etc.).
2. Required parameters: Specify what parameters will be controlled by the valve (e.g., liquid temperature, medium flow) and select the value ranges in which these parameters will change in the system.
3. Size and capacity: Select the appropriate valve size that will allow substances to flow through the system. The valve size should be compatible with the flow of the medium.
4. Valve type: Four-way valves come in various types, such as ball valves, rotary valves, and shaped valves. The type that best suits the characteristics of the medium and system requirements should be selected.
5. Material: The material from which the valve is made, depending on the type of medium with which it will work (e.g., stainless steel, bronze, cast iron), should be selected.
6. Control: One should decide whether the valve will be controlled manually or automatically. In some systems, automatic control can be more effective and precise.
7. Application: One should ensure that the valve selected will be suitable for the specific application and whether it will be temperature control in an HVAC system or flow regulation in an industrial installation.
8. Energy efficiency: For HVAC or other systems in which energy efficiency is important, one should select a valve with low-pressure loss and a well-matched flow profile.

To sum up, selecting the appropriate four-way valve requires understanding the system requirements and adapting the valve parameters to the specifications and characteristics of the medium.

Mixing valves are a standard element of fittings in heating installations in which several heating circuits are designed. Often, underfloor heating, radiator heating and, of course, domestic hot water circulation are planned in one heating installation. Mixing valves will be necessary to ensure the appropriate temperature of the medium in each of these circuits. The designed valve functions automatically, so regardless of the hot and cold-water parameters, the temperature is regulated automatically as the valve strives to maintain the set temperature value. If the flow of any water stream is disturbed, the outflow will be closed. This solution ensures the safety of users of the installation and will protect against burns, e.g., in public buildings and during thermal disinfection of the installation. Another advantage is that this cheap and effective solution does not require electricity. After establishing the temperature set point, the valve will ensure a constant outlet temperature. This type of valve is also an effective protection structure for solid fuel boilers and protects the boiler against return temperatures that are too low. As a result, it improves the initial efficiency of the boiler and extends its operating time. This is due to its ability to maintain an appropriately high return temperature and prevent the boiler from cooling down. This eliminates condensation of water vapor contained in exhaust gases.

Analyzing the literature on the subject, the authors come to the conclusion that the current design of the four-way valve can be improved with the use of software that allows detailed examination of liquid flow channels in terms of various technical specifications.

The design of the structure assumes a fast switching time of less than 5 milliseconds between the open and closed positions and generates minimal pressure drops even at high currents in order to prevent energy dissipation. The desired target will be able to achieve a maximum pressure drop of 15 bar at a flow rate of 60 L/min. In addition, the valve design will be characterized by reliability and the ability to handle multiple operating cycles without compromising its durability.

The problem of optimal design implementation via the principles of energy transformation has prompted the authors to develop a four-way valve design and apply it to household conditions while respecting the environment and natural resources and the conforming to the requirements of national and EU law as part of Poland's energy transformation.

3. Materials and Methods

3.1. Design Stages of a Four-Way Valve

The four-way valve was designed in SolidWorks. This valve has the following parameters [6]:

- Gross weight: 3325 kg.
- Net weight: 3300 kg.
- Capacity: 5598 dm^3.
- S-type flow characteristics.
- Nominal pressure: 10 bar.
- Construction materials, DZR brass CuZn36Pb2AS (602N).

The design was based on technical documents and standards containing information on the structure of the body, liquid flow ports, types of threading, and control of the intensity and direction of medium flow. Thanks to the possibility of building assembly drawings, the analyzed project will include a movable adjustment connection with the valve body in the form of an adjustment lever, the diagram of which is shown in Figure 3.

Figure 3. Diagram of the replaceable lever for a four-way valve. Source: own study.

The four-way valve is the object of research in this work. It was designed using SolidWorks software to understand its operation, present the flow of the medium, and analyze its structure and functionality. The valve design allows for the necessary strength simulations and analysis of the problem of evaporator frosting.

The research included the following:

- Valve design in SolidWorks.
- Four-way valve tests: cause-and-effect analysis of potential defects in the designed structure (FMEA) and strength tests aimed at selecting material for the structure.
- Static analysis of a four-way valve within the framework of sustainable development.

For most of the part elements, solid modelling with features was used, using functions for sheet metal elements. Rolled elements were made using the functions of welded structures and their libraries of valves and shapes. When creating insulation elements, due to the need to adapt them to the existing valve geometry, extensive use was made of multi-object modelling and elements of Boolean algebra. There were no separate thermal models, and simplifications of the geometric model for computational purposes were made using the mechanism of part and assembly configuration, as well as operations on assemblies. The model was discretized using curvature-based meshes with assumed maximum and minimum element dimensions. For small elements with complex shapes, as well as where contact resistance occurred, the FEM mesh was refined on a small surface.

3.2. Cause and Effect Analysis of Potential Structural Defects (FMEA)

Failure mode and effects analysis (FMEA) is a cause-and-effect analysis presenting the most potential defects in construction elements or process phases. This analysis is used to identify potential problems in order to eliminate them in the future or to reduce the likelihood of their occurrence. It is worth adding that the analysis has a basic assumption that most errors result directly from the production process, and that their detection is low in the initial phase, so the described defects are a derivative of errors that occurred in the process of creating and constructing the four-way valve. For FMEA analysis, eight key elements of the overall valve design were specified:

- Valve body.
- Flow channels.
- Gate.
- Connection of the valve with the lever.
- Threading the connection to the installation.
- Manual lever.
- Actuator regulator.
- Sealing kit.

Each of the above elements is assigned the most probable potential defect, its type, effect and cause. The analysis presents the most appropriate control method for the type of defect assigned to a specific element. Monitoring of each element should be undertaken using an appropriate, special method of measurement and problem identification, due to the nature of the valve construction element. For example, an appropriate method for checking the condition of the valve body would be to analyze the strength of the structure and the construction material, while an appropriate method for checking the flow channels is to measure the pressure inside the valve. Specifying each control method allows one to take the most recommended, appropriate action that will have the most positive impact on the risk of a defect (R), the probability of detecting a defect (W) and the level and significance of the defect for the operation of the system (Z), of which the four-way valve is a part. The above indicators (R, W, Z) are subject to a scale from 1 to 10. The higher the value of the indicator, the greater the probability of a defect occurring (R), the greater the probability of not detecting it (W) and the greater its importance for the correct operation of the system (Z). Based on the assessment of the criticality of each indicator of all elements separately, the following formula is derived:

$$RPN = R \times Z \times W \quad (1)$$

Risk priority number (RPN) is an indicator that takes into account the three previous indicators R, W, and Z. The maximum (1000) and minimum (1) values of this indicator are determined by the presented scale. The higher the RPN value, the greater the overall risk associated with a specific valve element.

3.3. Strength Tests in SolidWorks Software

SolidWorks simulation is an intuitive tool designed to perform quick strength simulations of finished products while maintaining the high reliability of the results. The main advantages of the software include the following:

Heat transfer analysis:

- Calculation of heat flow in adiabatic wall approximations or solid objects.
- Determination of different types of heat sources.
- Assigning models a wide range of solid materials, stored in the engineering database.
- Defining one's materials by assigning them values for such physical properties as thermal conductivity, heat capacity, etc.
- Calculation of radiant heat. The engineering database includes radiating surfaces such as blackbody walls, whitebody walls, graybody with any albedo, and a wide range of real material surfaces.

Types of flows and fluids:

- Flow analysis of up to ten different types of fluids (liquids, gases/vapors, real gases, non-Newtonian fluids and compressible fluids). The database contains many fluids with defined properties.
- Analysis of a problem containing many fluids of different types, provided that the areas of different fluids are separated from each other using fluid subdomains.
- Fluid mutual dilution analysis. The mixing fluids must be of the same type.
- Definition of the fluids.

As part of the strength tests, a numerical static analysis was performed to check the stresses and deformations of the designed valve. The calculations were made according to the Huber–Mises hypothesis, which states that only the part of the energy that is used for specific deformation has a decisive influence on the material effort. The results of these tests, in turn, allow for fatigue analysis to be carried out in order to determine the critical value of the load cycle at which the structure will fail.

4. Results and Discussion

4.1. Design Stages of a Four-Way Valve

The four-way valve was designed using solid modelling (in SolidWorks software). This consists of a body part of the entire block and a valve with a lever. Both structural elements, integrated into the assembly drawing, make up the structure of the four-way valve. Thanks to the program's capabilities, the research included various solutions for the modification of the dimensions, structure, shape and design operations of the analyzed valve [45]. The performed tests allowed us to obtain optimal shape, structure and strength parameters. The entire design of the four-way valve consists of the following structural elements: a shutter with a lever, a body and an alternative design of the shutter with an actuator regulator. Figure 4 shows the design of a four-way valve.

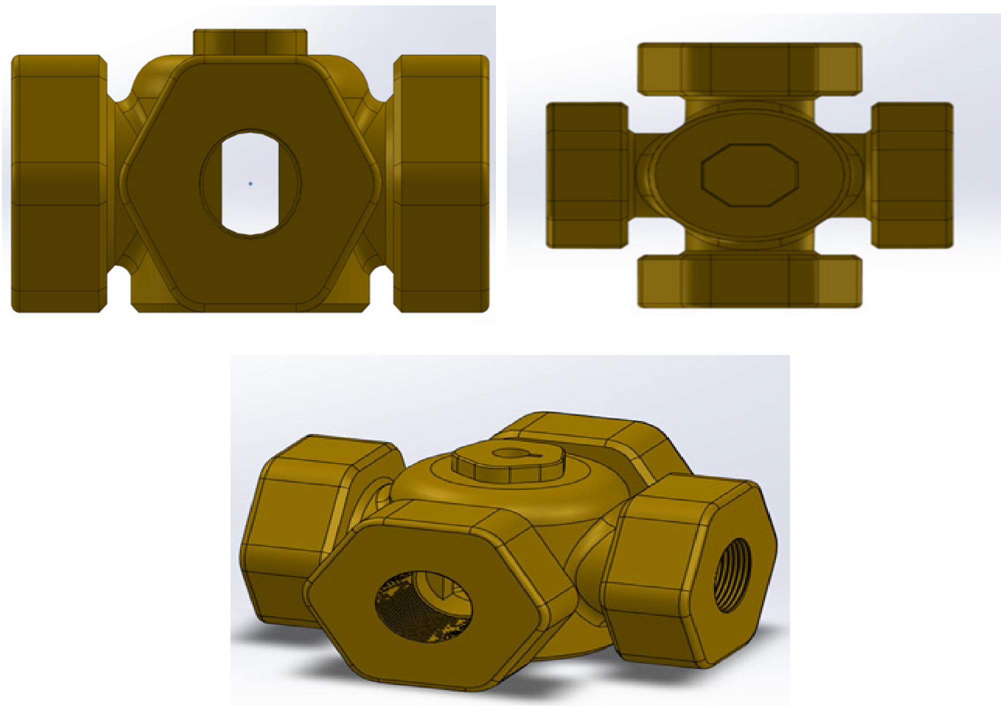

Figure 4. Four-way valve design. Source: own study.

As part of the research, we undertook the innovative design of a shutter with a lever, shown in Figure 5, and of a shutter with an actuator controller, the assembly drawings of which are shown in Figure 6.

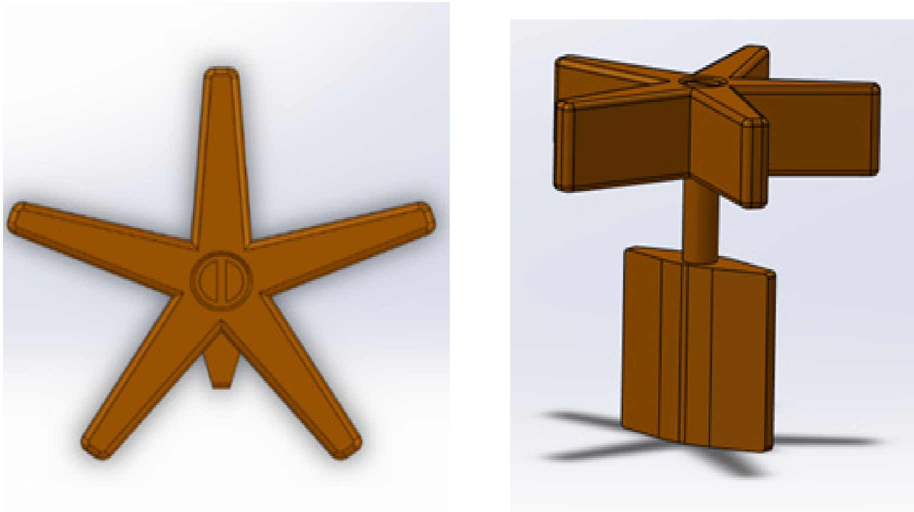

Figure 5. Design of a lever shutter. Source: own study.

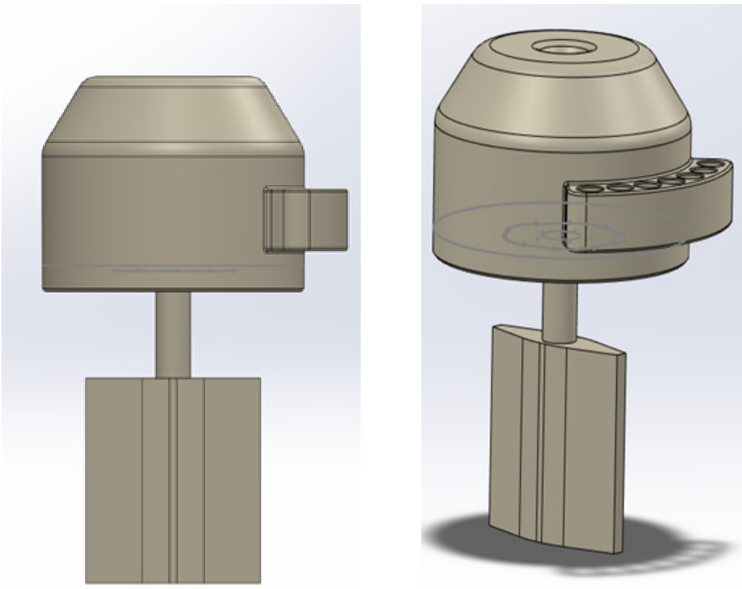

Figure 6. Design of a shutter with an actuator controller. Source: own study.

Body design stages:

As part of this part of the research, a design of the four-way valve body structure was made. The design process consisted of 22 construction stages. These stages included information about the dimensioning used, relationships between sketch elements, operation parameters, etc. Due to the extensive scope and number of design drawings made at this stage, the authors present only the most important design results, which are schematically presented in Figure 7.

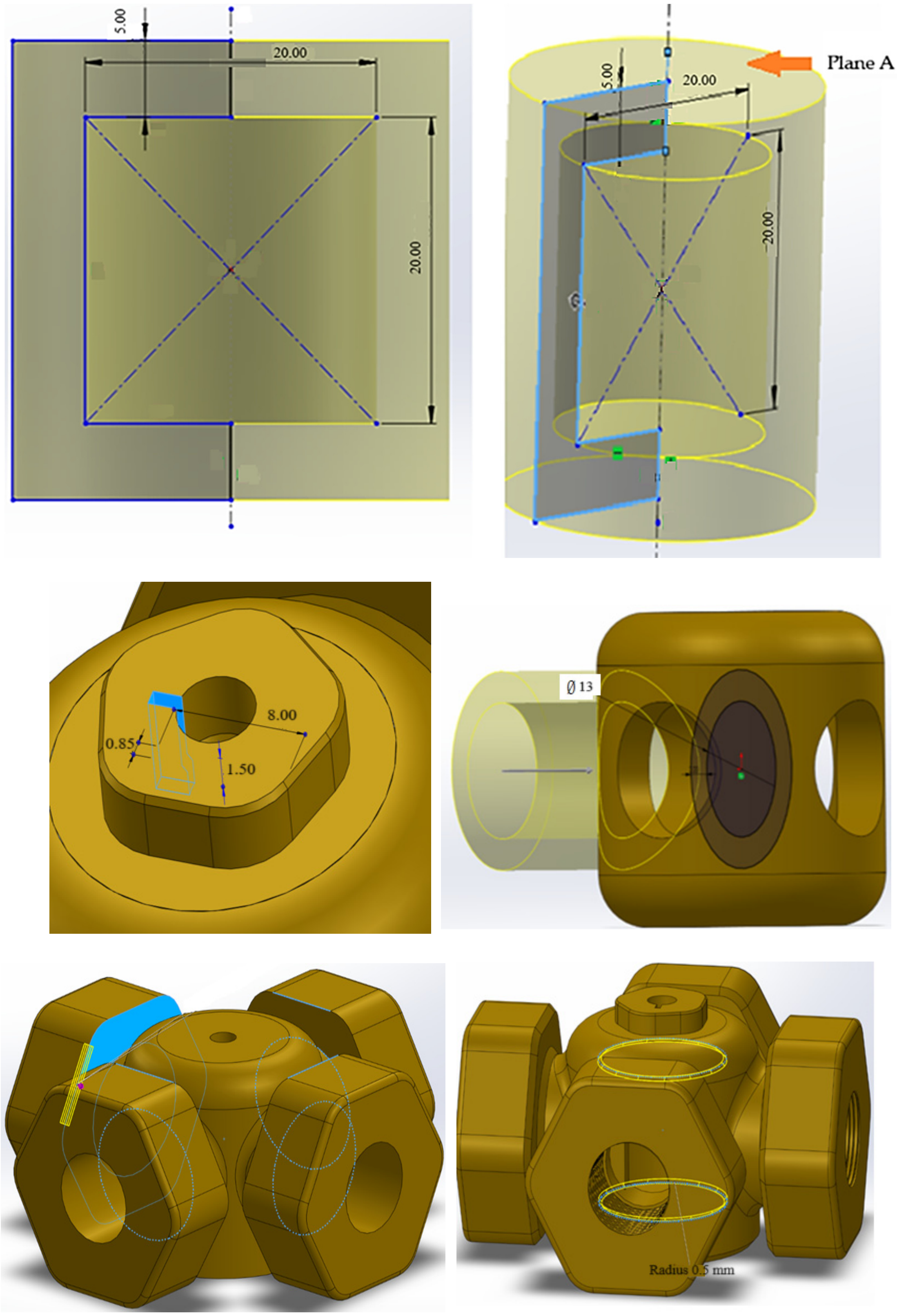

Figure 7. Body design stages. Source: own study.

In the further part of the research, the stages involved in designing a basic gate with a lever are presented schematically, as shown in Figure 8.

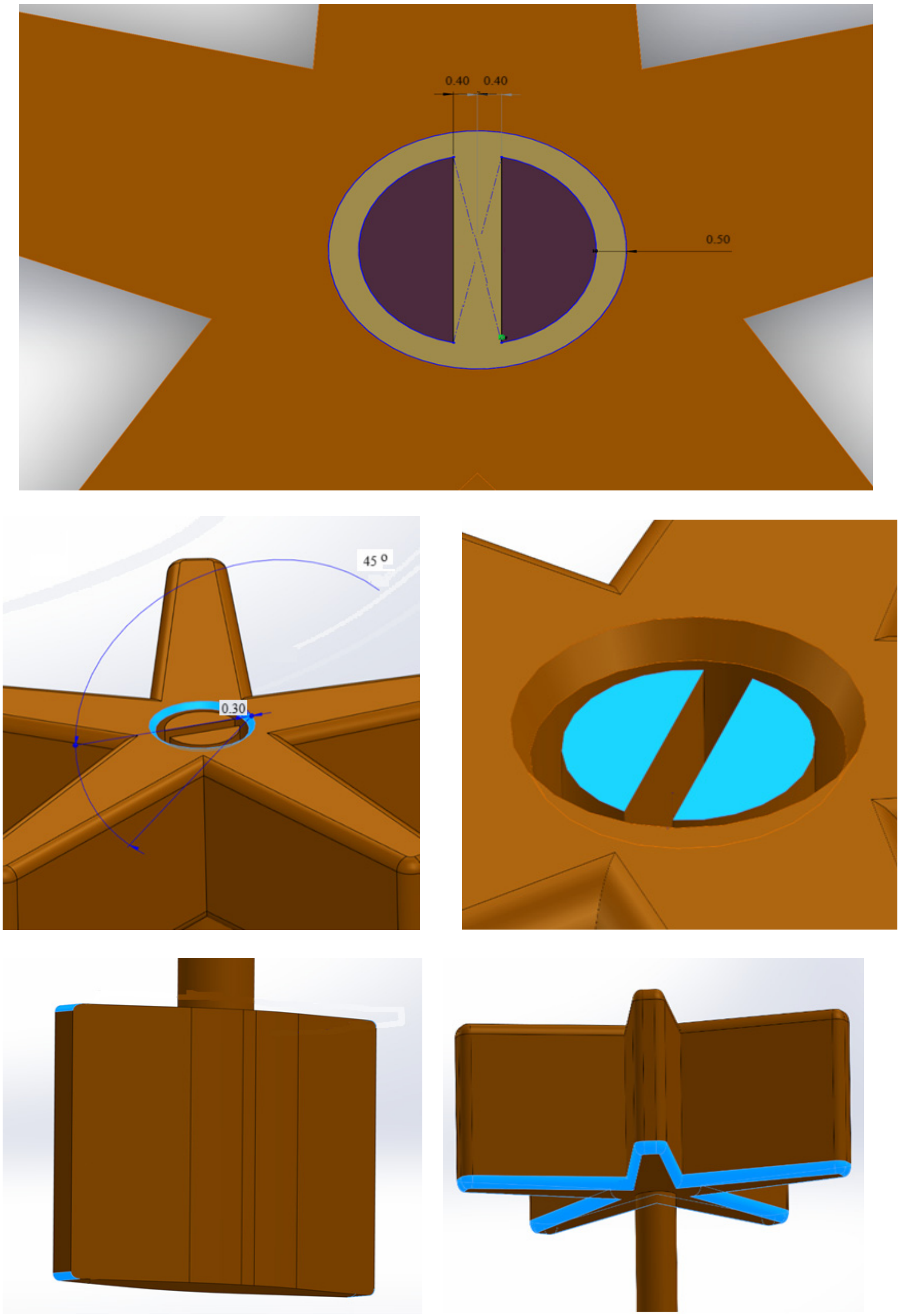

Figure 8. Design stages of a basic lever shutter. Source: own study.

The design research is complemented by a schematic presentation, shown in Figure 9, of the stages involved in designing an alternative valve shutter with a regulator. The design proposed by the authors, compared with the traditional design, is characterized by the lack of a lever, which is replaced by a controller regulator, i.e., an automatic option for controlling the medium flow.

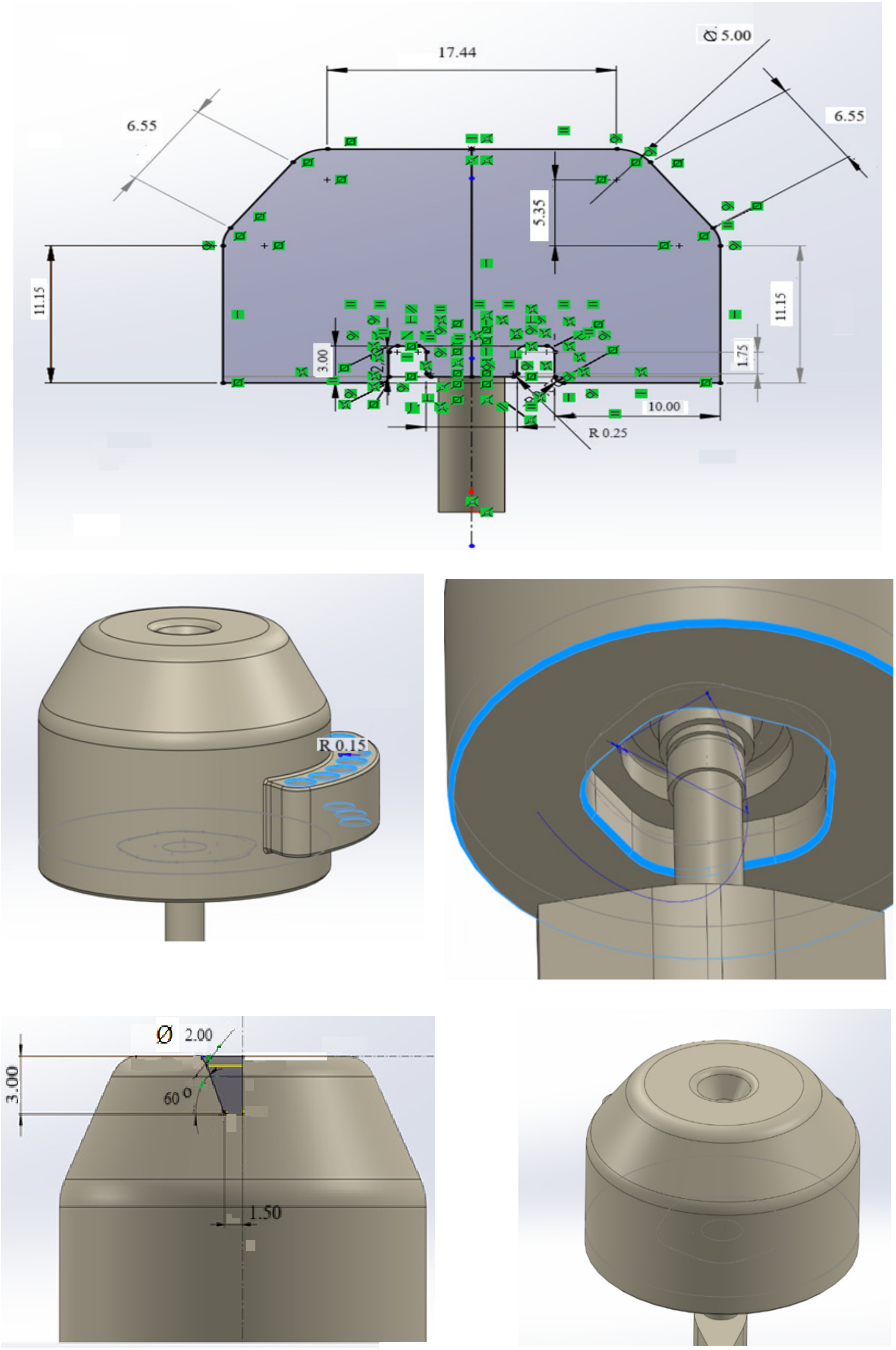

Figure 9. Stages involved in designing a valve plug with a regulator. Source: own study.

The result of this part of the research is the design of the following parts: a four-way valve body, valve shutters with a lever and valve shutters with a regulator. These parts consist of two versions of the four-way valve design, one with a manual lever and one with a regulator. The mass properties of the two design versions are shown in Figure 10.

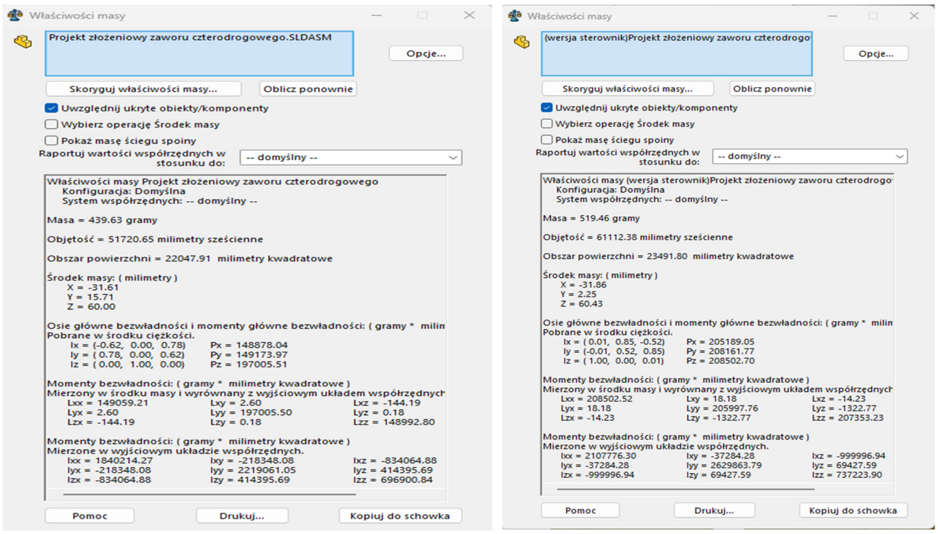

Figure 10. Mass properties of two versions of the four-way valve. Source: own study.

Figure 11 shows an isometric projection, a two-dimensional axonometric projection, a three-dimensional axonometric projection and a front, lower and right-side projection of the designed solid with cross-sections A-A and cross-section B-B. Figure 12 shows the significant dimensions of the four-way valve design in cross-section A-A.

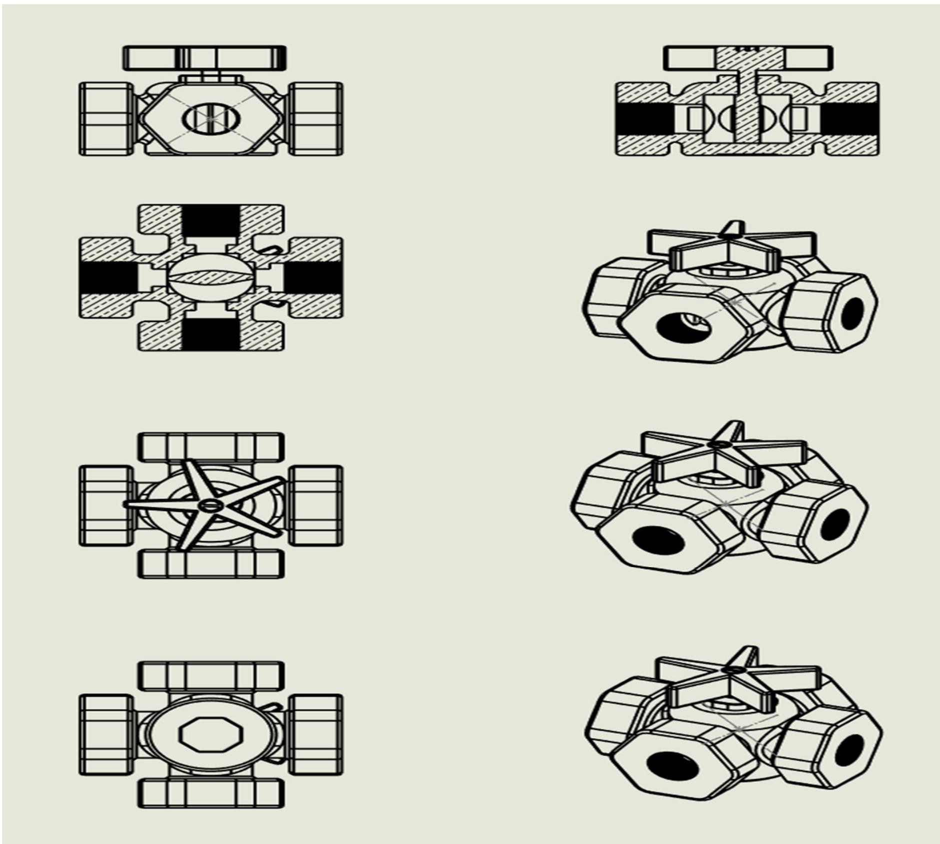

Figure 11. Views and cross-sections of a four-way valve. Source: own study.

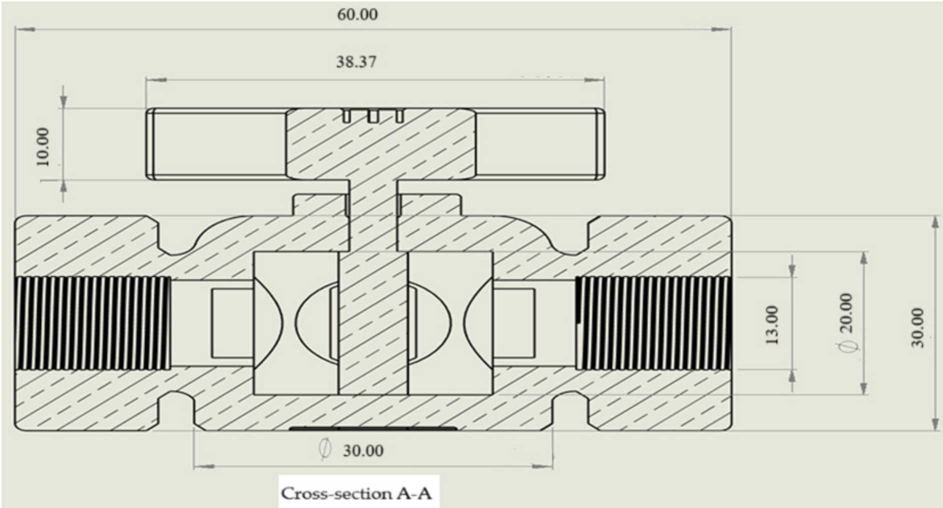

Figure 12. Important dimensions of a four-way valve. Source: own study.

4.2. Cause and Effect Analysis of Potential Structural Defects (FMEA)

FMEA objectives are consistent with the principle of "continuous improvement". The FMEA method allows one to subject a product or process to subsequent analyses, and then, based on the results obtained, introduce corrections and new solutions, effectively eliminating sources of defects. Analyses can provide new ideas with which to optimize product properties. Analyses can be performed for the entire product, a single component or structural element of the product, as well as for the entire technological process or any of its operations. The most frequently used is FMEA analysis of a product/structure or production process. FMEA analysis of the product/structure is carried out during preliminary design work in order to obtain information about the strong and weak points of the product, so that conceptual changes can be introduced even before the actual construction and technological work are undertaken. FMEA analysis of the production process is performed in order to identify factors that may hinder compliance requirements contained in the design specification (product design drawing) or disorganize the production process.

Our research has presented an analysis of potential defects occurring during the design process of a four-way valve. Table 1 presents the interpretation of the scale and the type of defect in a way that allows the FMEA indicators to be translated into an evaluation of the element's defect in terms of the probability of their occurrence. Table 2 presents the FMEA analysis of the four-way valve components.

The marked difference in RPN is most significant for the seal kit. This was due to the use of the control method listed in the table, which reduced the level of the *R* and *W* indicators by two points on the FMEA analysis scale. The next elements whose *RPN* indicator decreased significantly are the actuator regulator and the shutter. The actuator controller control method differs from other methods due to the electrical component of the actuator and the regulator, which is the reason for most problems of this type. This is in contrast with mechanical elements, where the dominant type of defects are design errors and the neglect of moving and connection elements. The general conclusion from the analysis of the four-way valve elements most susceptible to wear and failure is an almost two-fold decrease in the summed *RPN1* index compared with the summed *RPN2* index, where

$$RPN1 = \mathrm{RPNKZ1} + \mathrm{RPNKP1} + \mathrm{RPNZ1} + \mathrm{RPNPZD1} + \mathrm{RPNGPI1} + \mathrm{RPNDM1} + \mathrm{RPNRS1} + \mathrm{RPNZU1}$$

$$RPN2 = \mathrm{RPNKZ2} + \mathrm{RPNKP2} + \mathrm{RPNZ2} + \mathrm{RPNPZD2} + \mathrm{RPNGPI2} + \mathrm{RPNDM2} + \mathrm{RPNRS2} + \mathrm{RPNZU2}$$

$$RPN1 = 794 > RPN2 = 414$$

Table 1. Interpretation table—FMEA analysis.

Speech	FMEA of the Valve Element	R-Value	Probability of Occurrence
	R index		
Unbelievable	The occurrence of a defect is unlikely	1	less than 1 in 1,000,000
Very rarely	There are relatively few defects	2	1 in 20,000
Rarely	There are relatively few defects	3	1 in 4000
On average	The defect occurs sporadically from time to time	4–6	1 in 1000
Often	The defect repeats itself cyclically	7–8	1 in 40
Very often	The flaw is almost impossible to avoid	9–10	1 in 8
Defect Detectability	The Probability of Detecting a Defect		*W*
	W index		
Very high	Very low probability of not detecting a defect before the product leaves the manufacturing process. Automatic inspection of 100% of elements, and installation of protection.		1–2
High	Low probability of failure to detect a defect		3–4
Average	Medium Probability of not detecting a defect		5–6
Low	The probability of not detecting a defect		7–8
Very low	The probability of not detecting a defect		9–10
	The Importance of the Defect for the Customer		*Z*
	Z index		
Very small	Minimal effect, the customer does not notice anything, and the defect does not have any impact on the conditions of the use of the product		1
Small	Minimal effect, causing minor disruption. A moderate deterioration in the product's properties may be noticeable.		2–3
Average	The defect causes limited dissatisfaction and causes little inconvenience. The product does not meet the needs or is a source of nuisance. The user notices the product's shortcomings.		4–6
High	Customer dissatisfaction occurs. Repair cost unknown		7–8
Very high	High customer dissatisfaction. High repair cost due to failure of the entire unit or component.		9
Very high	The significance of the defect is very high, it threatens the user's safety and violates the provisions of the standards.		10

Source: own study on based [15].

The use of four-way valve control methods requires the selection of an appropriate tool for the emerging problem. Due to the operation of the four-way valve with substances introduced into the system, it is necessary to regularly measure the pressure inside the valve body, monitor the operation of the shutter (by reading the parameters on the actuator indicator, if a regulator is connected to the four-way valve), and check the tightness (usually carried out using special foam to locate the place of gas leakage, which occurs as a result of the pressure difference in the valve and the external environment).

The most potential errors mentioned in the FMEA analysis are also symptoms of an incorrect stage of design, construction and selection of the appropriate material. Therefore, it is important to carry out strength tests and solid geometry analysis to reduce the probability of a possible defect to a minimum.

Table 2. FMEA analysis of four-way valve components.

No.	Element of Construction	Potential Defect	Effects of the Defect	Cause of the Defect	Control Methods Used	Current Status				Recommended Actions Taken	Results of Actions			
						R	*W*	*Z*	*PR*		*R*	*W*	*Z*	*PR*
1	Valve body	Corrosion, deformation of the structure	Refrigerant leaking outside the system	Inappropriate material	Strength analysis of the material used	2	2	10	40	Selection of corrosion-resistant material	1	2	10	20
2	Flow channels	Blocked medium flow	Interruption of the operation of a system that includes a four-way valve	Inadequate pressure or dimensions of the valve interior	Valve interior pressure measurement	3	2	9	54	Valve maintenance	2	2	9	36
3	Mirror	Seizure, stuck, limited mirror movement	Limitation or loss of control over the factor introduced into the system	Design errors, inappropriate material, lack of lubrication	Compatibility analysis of moving parts	5	4	9	180	Lubrication of moving parts	4	3	9	108
4	Connecting the mirror to the lever	Deformation (fractures, seizing, cracks), uncontrolled leakage	Loss of control over the valve seal	Inappropriate material, lack of seal between the moving part and the valve body	Valve geometry analysis	3	2	10	60	Protecting sensitive parts against wear	3	1	10	30
5	Threaded connections to the installation	Thread damage	Inability to connect the installation to the valve	Wrong way to install the installation	Visual inspection	6	2	7	84	Protecting sensitive parts against wear	6	1	7	42
6	Manual lever	Deformation, fracture	Loss of control over the valve seal	Lever design errors	Geometry and strength analysis	4	2	9	72	Replacing the lever	4	2	9	72
7	Actuator regulator	Actuator failure, loss of connection between the controller and the actuator	Loss of control over medium flow parameters	Too high voltage, humidity	Control of actuator operating parameters	6	2	9	108	Resetting actuator operating parameters	4	1	9	36
8	Sealing kit	Damage to the sealing set	Uncontrolled refrigerant leakage, pressure drop	Ageing, not replacing the seal kit	Measurement of pressure inside the valve, tightness check	7	4	7	196	Replacing the seal kit	5	2	7	70

Source: own study.

4.3. Strength Tests in SolidWorks Software

The analysis of the strength of the four-way valve was carried out in the SolidWorks software using "Static Analysis" [17,18]. This was undertaken in order to assess the stiffness and strength of the entire solid by examining the resulting deformations when a specific force is applied to a selected wall or edge of the object. To prepare for the described analysis, in the first step, it was necessary to build a mesh for the designed four-way valve, which is shown in Figure 13.

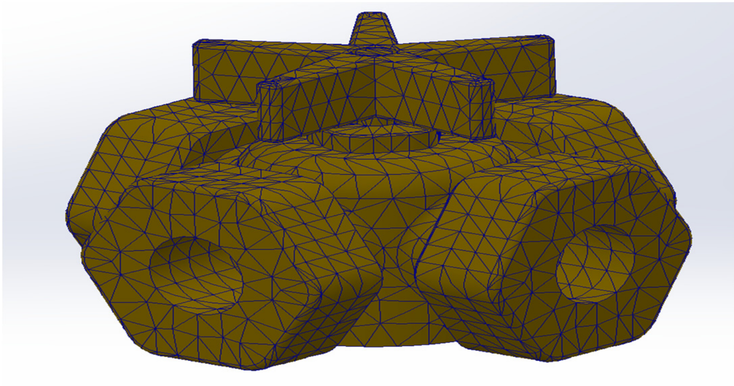

Figure 13. Design grid of a four-way valve. Source: own study.

The next step is to define the four-way valve body as "*Stationary Geometry*", the diagram of which is shown in Figure 14.

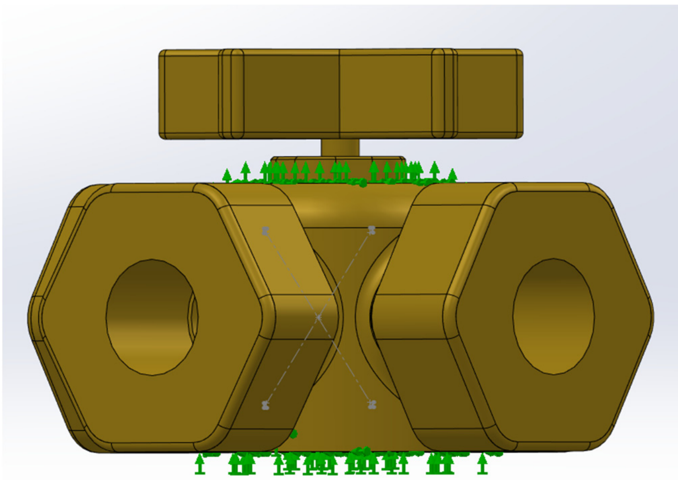

Figure 14. Defining the fixed geometry of a four-way valve. Source: own study.

A static solid analysis is performed for five selected materials of a four-way valve to investigate the level of deformations occurring when the same forces are applied to the same planes of the valve. The materials tested are brass, stainless steel, bronze, cast iron and aluminum. Table 3 shows the results of the static analysis. Two forces of 0.5 N were applied to the five selected materials on the plane of connection with the installation and on the plane of the closure separately. The result is represented by the stress (9 MPa) and the strain (*ESTRN*) that occurred as a result of the application of the above-mentioned force.

Table 3. Results of static analysis.

No.	The Value of the Applied Force, N	Type of Material	The Plane of Force Application	Result of Statistical Analysis	
				Tension (VON), MPa	Deformation (ESTRN)
1	0.5	Brass	The connection plane with the installation	0.01	5.40×10^{-8}
			Mirror plane	0.06	2.39×10^{-7}
2		Stainless steel	The connection plane with the installation	0.07	4.45×10^{-8}
			Mirror plane	0.06	2.44×10^{-7}
3		Brown	The connection plane with the installation	0.07	4.38×10^{-8}
			Mirror plane	0.06	2.15×10^{-7}
4		Cast iron	The connection plane with the installation	1.07×10^{4}	4.93×10^{-8}
			Mirror plane	6.43×10^{4}	2.15×10^{-7}
5		Carbon steel	The connection plane with the installation	1.09×10^{4}	2.58×10^{-8}
			Mirror plane	6.47×10^{4}	1.11×10^{-7}

Source: own study.

The presented results indicate the existence of significant differences in stress (VON) and strain (ESTRN). The differences result directly from the characteristics of the material—Poisson's ratio, tensile strength and yield strength. The results of this part of the research are presented in Table 4.

Table 4. Characteristics of the tested materials.

	Poisson's Ratio	Tensile Strength, MPa	Yield Strength, MPa
Brass	0.33	478.4	239.7
Stainless steel	0.27	685.0	292.0
Brown	0.30	55.1	275.7
Cast iron	0.31	861.7	551.5
Carbon steel	0.28	399.8	220.6

Source: own study.

The materials that show the greatest similarity in strain and stress values are bronze and stainless steel. Carbon steel and cast iron have lower stresses on the plane of the valve than on the plane of connection with the installation [46].

4.4. Four-Way Valve and Sustainable Development

The four-way valve plays a key role in minimizing energy consumption. Most often, mixing valves (also three-way valves) are an integral part of cooling/heating systems (heat pumps, air conditioning, ventilation, central heating of buildings). For this reason, optimization of the medium flow has the greatest impact on energy carriers, i.e., electricity, heat from the network, solar energy, geothermal energy, and energy from renewable sources. Figure 15 shows the level of energy consumption in Poland in 2023 in the European Union.

The presented data clearly show that, despite the constantly growing demand for energy, its overall consumption has slightly decreased. However, the level of energy consumption in systems using heat from the network, solar energy, ambient heat (heat pumps) and generally renewable energy, of which the four-way valve is a part, has increased visibly, which is related to the policy pursued by the European Union, the aim of which is to switch to this type of source of energy use. The optimization of refrigerant flow has become even more important and will become an even greater priority for sustainable development with each passing year. Buildings, the majority of whose energy consumption is generated by HVAC systems, account for approximately 40% of all energy consumed worldwide. It is possible to reduce energy consumption by approximately 30% by optimizing the installation of these systems, in particular the medium flow. A four-way valve with a connected actuator regulator creates a mechanism that is responsible for controlling the operating parameters of the system, the correct operation of which requires the attention of an experienced operator who can regularly check the reading and configure the process taking place inside the four-way valve by controlling the shutter. In HVAC systems, seemingly insignificant changes in operating parameters can often cause significant damage or a decrease in the efficiency of energy consumption. For example, in a heat pump installation, one degree Celsius of the medium temperature may cause a mixing of the supply and return water, which reduces the efficiency of the devices and ultimately negatively affects the user's thermal comfort. A temperature difference (in an air-conditioned room) of one degree on the Celsius scale also significantly affects operating costs, which can range as much as 12–18%. Therefore, it is important to constantly maintain the most optimal temperature due to the efficiency of the system, taking into account thermal comfort, which, according to research by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is between 23–26 °C in summer and 20–24 °C in winter, with typical clothing and activity of the people in the room.

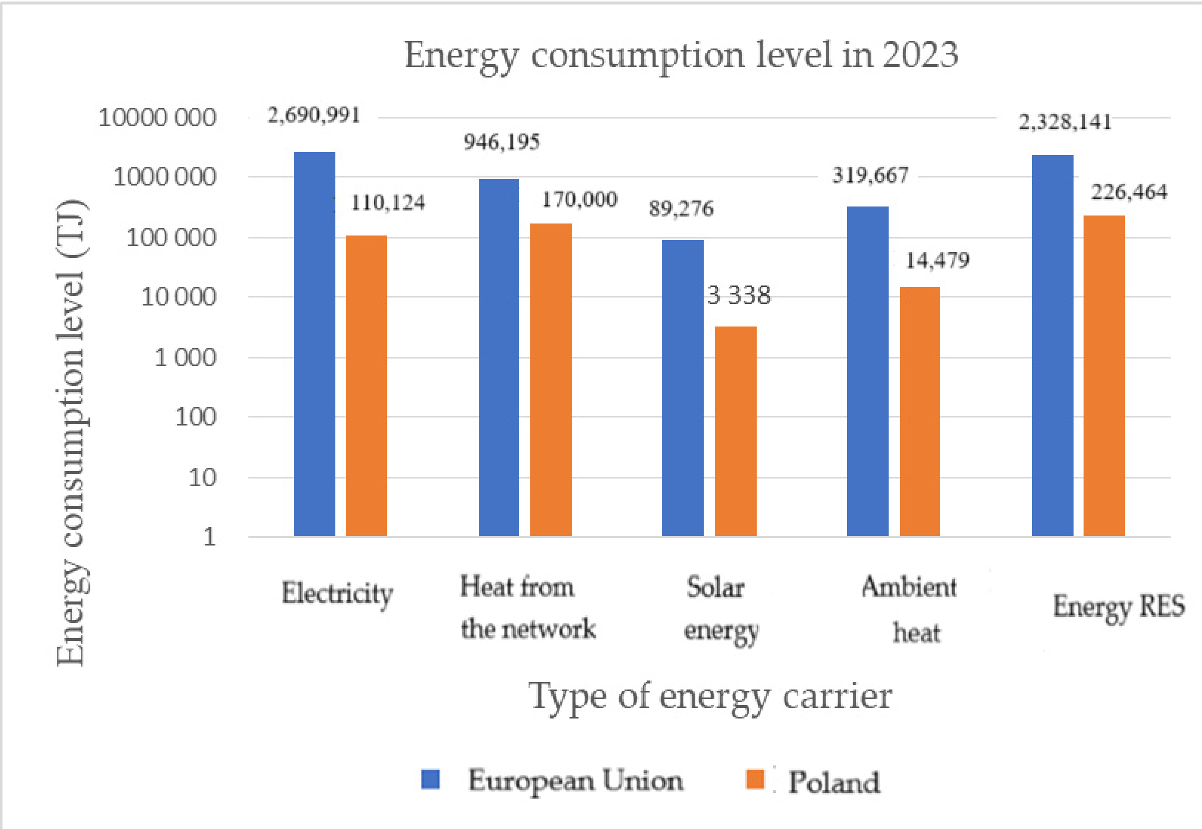

Figure 15. Levels of energy consumption in Poland and the EU. Source: own study, based on [24].

The four-way valve also affects, apart from the medium temperature, the flow rate. It is important to set the flow parameters to create the optimal flow of the medium in the system. Thanks to the ability to control the flow using a shutter, the operator can maintain a low temperature of the return water (below the dew point of water vapor), preventing the phenomenon of the overflow of the medium, which in turn shortens the condensation time, thus reducing the efficiency of the devices in the system. A consequence of the correct control of the medium flow is an equally important aspect of limiting the deposition of contaminants appearing inside the system installation. The uncontrolled flow of the medium often leads to the formation of this type of sediment, which creates resistance to heat transfer and therefore makes mixing the substances more difficult (the problem described in the FMEA analysis). Identifying such a problem automatically reads the actuator controller, resulting in thermal resistance that can be calculated based on the formula:

$$R_f = \delta/\lambda_f \tag{2}$$

where:

δ—material layer thickness,
λ_f—thermal conductivity coefficient,
R_f—thermal resistance of the material layer.

Table 5 shows the readings of the simulation results regarding the resulting thickness of the contamination layer of the refrigeration unit.

Table 5. Table of simulation results regarding the formation of pollutants.

Thickness of the Contamination Layer	0 mm	0.17 mm	0.35 mm
Coefficient of performance (COP)	2.84	−2.50%	−5.30%
Δp evaporator	53 kPa	3.10%	8.70%

Source: own study, based on [26].

Theoretically, central heating installations in a closed system are tight, which means that no contamination should arise in them. The appearance of contaminants can potentially damage expensive parts of the installation and reduce its efficiency. The most endangered element of the installation are thermostatic valves—these have a thermostatic element that dispenses the appropriate amount of warm and cooler medium to obtain the set temperature behind the valve. When dirt gets into the valve, this element will become blocked and proper temperature regulation will be impossible. A popular solution is a mesh filter. This works simply, by filtering the heating medium so that all impurities settle on the mesh, catching any impurities that are larger than the size of the mesh. The disadvantage is that, when the mesh is very dirty, the filter limits the flow in the installation, meaning that it needs to be cleaned regularly. One can also use a dirt separator. Due to its structure and internal filter element, the flow is slowed, causing contaminants to settle in its lower part. In addition, the separators have strong neodymium magnets that attract metal particles (filings, metal and rust particles). To properly protect the valve and the installation, a mesh filter (on the return from the installation) and a dirt separator should be installed.

The use of four-way valves is particularly important in heating, cooling and air conditioning systems, where precise control of temperature and fluid flow is crucial when seeking to achieve optimal performance and user comfort. These advanced valves not only enable precise mixing of liquids but also direct them to different areas of the system, which allows for effective temperature control in different zones of the building or installation. The four-way valve also fits various types of heating installations and can be used for steel boilers. These types of valves are durable and resistant to mechanical damage. Therefore, one does not have to worry that, for example, a temporary drop in temperature will translate into thermal comfort in the entire room. Brass valves also protect the thermostat. These types of valves protect against low-temperature corrosion, which could occur when the boiler operates at a low temperature and the medium-temperature heating is insufficient. In such a case, gases would condense in the combustion chamber, and, as we know, gases contain chemicals. Therefore, these might damage not only the installation but also the boiler. Additionally, corroded sheet metal could lead to uncontrolled exhaust gas flow, which poses a threat to health and life. The role of the four-way valve in the installation is very important, as it protects the boiler against low power, enables the creation of medium circulation, heats the liquid in the internal circuit and constitutes a barrier against water vapor condensation. The valve allows one to adjust the temperature, meaning that its use is therefore necessary for equipment protection and safety. It should also be mentioned that mixing valves prepare domestic hot water and give it priority during heating.

5. Conclusions

This article undertakes the task of developing a methodology for modeling popular hydraulic valves, such as four-way valves, using computer modeling methods. After analyzing the literature on the modeling of hydraulic valves and the structures presented in manufacturers' catalogs and patent descriptions, it was found that the geometry of the valve's working elements has a significant impact on the pressure and flow characteristics. Moreover, problems were found when calculating the hydraulic forces acting on the valve components. Therefore, the main emphasis in this work has been on developing an appropriate modeling methodology. Based on the analyses performed using SolidWorks computer programs, the following has been shown:

1. These methods are useful for analyzing flow phenomena occurring in valves commonly used in various hydraulic installations.
2. One can use the application programming interface (API) of SolidWorks programs to automate the process of shaping and optimizing the geometry of valve elements.
3. The values of hydraulic forces acting on valve elements determined in simulation tests are similar to those in the catalog. This allows us to conclude that the effects of the liquid's impact on the moving parts of the valve can be determined using the proposed simulation methods. It is possible to shape the pressure and flow characteristics of the valve by modifying the geometry of the valve elements.
4. Using simulation models, it is possible to correct the unfavorable impact of hydrodynamic values within a given range of volume flow rate.

Future conclusions:

1. The built models can be used for further analyses and development work.
2. The valve model will be subjected to measurements of hydraulic forces and may be further developed and focused on application work in order to further improve the design of valve components.
3. Analyses should be conducted in order to develop valve designs focused on new, ecological working media and construction materials.
4. Development of models correcting the unfavorable effects of hydrodynamic forces.

The direction of future research will be toward the physical creation of a valve model which is then subjected to laboratory tests. Its parameters will be checked on testing machines, strength charts will be constructed, its microstructure will be shown through microscopic examination and strength indicators will be calculated. In addition, its compatibility with various types of controllers will be checked in terms of smooth control, control of the valve pump operation, the possibility of controlling two other valves using additional modules, the possibility of connecting an internet module, return temperature protection and weather and weekly control. Once the model is completed, it will be configured with the controller and subjected to calibration and configuration tests.

Author Contributions: Conceptualization, M.N. and J.M.; methodology, M.N. and J.M.; software, M.N.; validation, M.N.; formal analysis, M.N.; investigation, M.N. and J.M.; resources, M.N.; data curation, M.N. and J.M.; writing—original draft preparation, M.N. and J.M.; writing—review and editing, M.N. and J.M.; visualization, M.N.; supervision, M.N. and J.M.; project administration, M.N. and J.M.; funding acquisition, J.M. All authors have read and agreed to the published version of the manuscript.

Funding: AGH University Krakow: Agreement No 16.16.200.396/B410.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

HVAC	Heating, ventilation, and air conditioning
GWP	Global warming potential index
ODP	Ozone depletion potential
CFC/HCFC	Refrigerants containing carbon and chlorine
HFC	Refrigerants containing carbon
CO_2/NH_3/HC	Factors of natural origin
HFO	Hydrogen fluoride refrigerants
KBZW1	Design of the basic four-way valve body
ZDZC1	Design of a basic gate with a lever
ZDZC2	Design of an alternative shutter with a regulator
FMEA	Failure mode and effects analysis

References

1. Yan, Q.; Li, D.; Wang, K.; Zheng, G. Study on the Hydrodynamic Evolution Mechanism and Drift Flow Patterns of Pipeline Gas-Liquid Flow. *Processes* **2024**, *12*, 695. [CrossRef]
2. Zheng, G.; Xu, P.; Li, L.; Fan, X. Investigations of the Formation Mechanism and Pressure Pulsation Characteristics of Pipeline Gas-Liquid Slug Flows. *J. Mar. Sci. Eng.* **2024**, *12*, 590. [CrossRef]
3. Finlayson-Pitts, B.J.; Pitts, J.N., Jr. *Chemistry of the Upper and Lower Atmosphere*; Elsevier Inc.: Amsterdam, The Netherlands, 2000; Volume 6, pp. 1–29.
4. Arora, C.P. *Refrigeration and Air Conditioning*; Tata McGraw-Hill Publishing Company Limited: New York, NY, USA, 2000; Volume 11, pp. 30–56.
5. Główny Urząd Statystyczny. *Poziom Zużycia Energii na Ogrzewanie w Gospodarstwach Domowych w Polsce*; Główny Urząd Statystyczny: Warsaw, Poland, 2021.
6. Danfoss Poland Product Store. *HRB 4, 40.00 m³/h, Rp 2, Zawory do Układów Centralnego Ogrzewania, Zawory Obrotowe, Zawory Regulacyjne z Siłownikiem Elektrycznym, Climate Solutions dla Ogrzewnictwa*; Danfoss Poland Product Store: Warsaw, Poland, 2024.
7. Andrew, D.; Althouse, C.H.; Turnquist, I.; Alfred, F. *Bracciano, Modern Refrigeration and Air Conditioning*, 18th ed.; Goodheart-Willcox: Tinley Park, IN, USA, 2019; Volume 7, pp. 30–65.
8. Tomczyk, J.; Silberstein, E.; Whitman, W.C.; Johnson, W.M. *Refrigeration and Air Conditioning Technology*; Cengage Learning: Boston, MA, USA, 2016; Volume 10, pp. 30–48.
9. Niekurzak, M. The Potential of Using Renewable Energy Sources in Poland Taking into Account the Economic and Ecological Conditions. *Energies* **2021**, *14*, 7525. [CrossRef]
10. American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook—HVAC Systems and Equipment, 9, 19, 20, 24*; ASHRAE: Peachtree Corners, GA, USA, 2020.
11. Mitchell, J.W.; Braun, J.E. *Principles of Heating, Ventilation, and Air Conditioning in Buildings*; John Wiley & Sons: Hoboken, NJ, USA, 2014; Volume 8, pp. 1–40.
12. McQuiston, F.C.; Parker, J.D.; Spitler, J.D.; Taherian, H. *Spitler, Heating, Ventilating and Air Conditioning Analysis and Design*, 6th ed.; Wiley: Hoboken, NJ, USA, 2023; Volume 9, pp. 4–50.
13. Gohari, H. *Air Conditioning and Refrigeration Repair Made Easy*; Xlibris Corp.: Bloomington, IN, USA, 2009; Volume 6, pp. 20–56.
14. Afriso Sp. Z o. o. Sterownik Delta 2003d + Siłownik Proclick, str. 69. 2023. Available online: https://sterownikitech.pl/zestaw-afriso-sterownik-i-silownik-z-zestawem-montazowym,id1136.html (accessed on 10 January 2024).
15. Soliński, B. Analiza Przyczyn Wadliwości i Krytyczności Wad. Available online: https://www.zarz.agh.edu.pl/bsolinsk/fmea.html (accessed on 10 January 2024).
16. Mikulak, R.J.; McDermott, R.; Beauregard, M. *The Basics of FMEA*; CRC Press: Boca Raton, FL, USA, 2017; Volume 5, pp. 23–47.
17. Tomczyk, J. *Troubleshooting and Servicing Modern Air Conditioning and Refrigeration Systems*, 2nd ed.; Esco Press: Essex, UK, 1995; Volume 3, pp. 1–68.
18. Niekurzak, M.; Mikulik, J. Modeling of Energy Consumption and Reduction of Pollutant Emissions in a Walking Beam Furnace Using the Expert Method—Case Study. *Energies* **2021**, *14*, 8099. [CrossRef]
19. Zawadzki, P. *Engineering Analysis with SOLIDWORKS Simulation*; SDC Publications: Mission, KS, USA, 2022; Volume 5, pp. 1–47.
20. George, F. *Limbrunner i Craig D'Allaird, Applied Statics and Strength of Materials*, 6th ed.; Pearson: London, UK, 2015; ISBN 9780133840544.
21. Roberta, H. *King, Finite Element Analysis with SOLIDWORKS Simulation*, 1st ed.; Cengage Learning: Boston, MA, USA, 2018; Volume 2, pp. 1–32.
22. Kubiński, W. *Materiałoznawstwo. Tom 1. Podstawowe Materiały Stosowane w Technice*; Wydawnictwo AGH: Kraków, Poland, 2012; pp. 1–155.
23. Chartered Institution of Building Services Engineers. *Energy Efficiency in Buildings: CIBSE Guide F*; CIBSE: London, UK, 2012; Volume 2, pp. 1–30.

24. Główny Urząd Statystyczny. Zużycie Energii w Gospodarstwach Domowych w Podziale na nośniki Energii w Polsce i Krajach Unii Europejskiej oraz udział Poszczególnych Krajów w Zużyciu Energii w UE-28. 2021. Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/zuzycie-energii-w-gospodarstwach-domowych-w-2021-roku,12,2.html (accessed on 15 January 2024).
25. Lechner, N. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2008; ISBN 0470048093.
26. IMI Hydronic Engineering, Efektywność Energetyczna Instalacji Hydraulicznych, Breakthrough Engineering, 2–55. Available online: https://www.imi-hydronic.com/pl-pl (accessed on 10 January 2024).
27. Niekurzak, M.; Lewicki, W.; Drożdż, W.; Miązek, P. Measures for Assessing the Effectiveness of Investments for Electricity and Heat Generation from the Hybrid Cooperation of a Photovoltaic Installation with a Heat Pump on the Example of a Household. *Energies* **2022**, *15*, 6089. [CrossRef]
28. Olczak, P.; Olek, M.; Matuszewska, D.; Dyczko, A.; Mania, T. Monofacial and Bifacial Micro PV Installation as Element of Energy Transition-The Case of Poland. *Energies* **2021**, *14*, 499. [CrossRef]
29. Tamburrano, P.; Plummer, A.R.; Distaso, E.; Amirante, R. A review of electro-hydraulic servo valve research and development. *Int. J. Fluid. Power* **2019**, *20*, 53–98.
30. Tamburrano, P.; Plummer, A.R.; Distaso, E.; Amirante, R. A review of direct drive proportional electrohydraulic spool valves: Industrial state-of-the-art and research advancements. *J. Dyn. Syst. Meas. Control Trans. ASME* **2019**, *141*, 020801. [CrossRef]
31. Zhu, Q.; Huang, D.; Yu, B.; Ba, K.; Kong, X.; Wang, S. An improved method combined SMC and MLESO for impedance control of legged robots' electro-hydraulic servo system. *ISA Trans.* **2022**, *130*, 598–609. [CrossRef]
32. Chen, X.; Jiao, Z.; Liu, X.; Li, X.; Qi, P.; Shang, Y. Experimental validation of a practical nonlinear control method for hydraulic flight motion simulator. *J. Frankl. Inst.* **2022**, *359*, 2405–2423. [CrossRef]
33. Fan, Y.L.; Lei, Y.; Zhang, J.W.; Wang, J.; Li, Z. Flow Force of Pressure Independent Control Valve with Different Valve Core Structural. *J. Phys. Conf. Ser.* **2020**, *1634*, 12149. [CrossRef]
34. Li, R.; Sun, Y.; Wu, X.; Zhang, P.; Li, D.; Lin, J.; Xia, Y.; Sun, Q. Review of the Research on and Optimization of the Flow Force of Hydraulic Spool Valves. *Processes* **2023**, *11*, 2183. [CrossRef]
35. Gao, Q.; Wang, J.; Zhu, Y.; Wang, J.; Wang, J. Research Status and Prospects of Control Strategies for High Speed on/off Valves. *Processes* **2023**, *11*, 160. [CrossRef]
36. Wang, H.; Chen, Z.; Huang, J.; Quan, L.; Zhao, B. Development of high-speed on-off valves and their applications. *Chin. J. Mech. Eng.* **2022**, *35*, 67. [CrossRef]
37. Karpenko, M.; Stosiak, M.; Šukevičius, Š.; Skačkauskas, P.; Urbanowicz, K.; Deptuła, A. Hydrodynamic Processes in Angular Fitting Connections of a Transport Machine's Hydraulic Drive. *Machines* **2023**, *11*, 355. [CrossRef]
38. Li, L.; Gu, Z.H.; Xu, W.X.; Tan, Y.F.; Fan, X.H.; Tan, D.P. Mixing mass transfer mechanism and dynamic control of gas–liquid–solid multiphase flow based on VOF-DEM coupling. *Energy* **2023**, *272*, 127015. [CrossRef]
39. Ge, M.; Zheng, G.A. Fluid-solid mixing transfer mechanism and flow patterns of the double-layered impeller stirring tank by the CFD-DEM method. *Energies* **2024**, *17*, 1513. [CrossRef]
40. Borowski, P. Adaptation strategy on regulated markets of power companies in Poland. *Energy Environ.* **2019**, *30*, 3–26. [CrossRef]
41. Kochanek, E. *Wielowymiarowość Interesów Energetycznych w Dobie Transformacji Systemowej*; WAT: Warsaw, Poland, 2021.
42. Niekurzak, M.; Kubińska-Jabcoń, E. Analysis of the Return on Investment in Solar Collectors on the Example of a Household: The Case of Poland. *Front. Energy Res.* **2021**, *9*, 224. [CrossRef]
43. *Polityka Energetyczna Polski 2040, Załacznik do Uchwały nr 22/2021 Rady Ministrów z Dnia 2 Lutego 2021 r*; Ministerstwo Klimatu i środowiska: Warsaw, Poland, 2021.
44. Szczerbowski, R. The forecast of Polish power production sector development by 2050—Coal scenario. *Energy Policy J.* **2018**, *19*, 5–18.
45. Figołuszka, S. Projekt zaworu Czterodrogowego do Instalacji Centralnego Ogrzewania Budynków z Wykorzystaniem Modelowania Bryłowego. Engineering Thesis, AGH, Kraków, Poland, 2023, unpublished materials.
46. Robaina, M.; Neves, A. Complete decomposition analysis of CO2 emissions intensity in the transport sector in Europe. *Res. Transp. Econ.* **2021**, *87*, 101074. [CrossRef]