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Research Article

Hydrodynamic behaviour improvement of check valves through CFD analysis

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ABSTRACT

In this article, the computer assisted design, flow simulation, optimization of production parameters and unique design prototype manufacturing of a check valve with 16 bar pressure, 5 m/s flow rate and 52000 m^3/h flow coefficients, which have never been achieved before in the valve sector, were presented to the attention of the readers. Check valves have a critical role that do not allow reverse flow of the fluid passing through them and are generally designed to secure the pipeline. A small mistake in design may cause great damage in the system. For this reason, a new product of which the disc material exposed to 5 m/s fluid velocity, the body subjected to 16 bar pressure and the system with a flow coefficient of 52000 m^3/h were designed by the SolidWorks, the flow was simulated with CFD (Computational Fluid Dynamics), and the mechanical resistance was analysed by FEA (Finite Element Analysis). Fluent, CFD and mechanical modules of ANSYS were used to define the parameters of the design. The manufactures of the products designed in the computer environment have been produced by casting method with a 45% ferritic microstructure and impact resistance twice as high as the standard requirements have been implemented.

1. Introduction

Check valves are one-way safety valves that prevent the fluids passing through the installation from moving in one direction and returning, thus allowing the system to operate more efficiently [1]. Check valves are simple devices. They perform a vital function by preventing reverse flow. Possible reverse flow in the system can often cause damage or malfunction to other equipment connected to the installation, such as valves and pumps [2]. Even if there is no malfunction, it may cause loss of system integrity. The operation of the check valve, which has a single inlet and outlet, is based on pressure difference. The valve opens when the pressure from the inlet side is greater than the pressure from the outlet side. If the pressure in the inlet direction is lower than the pressure in the outlet direction, it closes, and the fluid is prevented from returning [3]. Check valves do not require a lever, actuator, or human power, unlike the opening and closing principle of other valve types. Closing and opening is completely automatic [4-7].

There are more than one check valve type depending on the system in which it will be used. The selection should be made according to factors such as type of fluid, operating method, installation direction, maximum pressure, connection point, temperature, closing speed. The main types are swing check valve, wafer check valve, spring check valve, tilting check valve, ball check valve, dual check valve [8-12].

A check valve requires a minimum pressure between the inlet and outlet to operate [13-16]. This lowest pressure, which causes the valve to open, is called cracking pressure. This required minimum pressure varies depending on the size and design of the check valve [17]. When choosing a check valve, it should be noted that the system can produce this pressure [18].

If the flow pressure in the system drops below the separation pressure or a reverse flow occurs, the check valve will close. The closing mechanism inside the check valve varies depending on the type [19]. In all cases, the mechanism inside the check valve will prevent backflow and provide sealing [20].

As the they operate through a single way, it is very important to install them in the correct direction to the installations to be used [21]. If installed in the opposite direction, flow will stop and cause pressure build-up. This causes damage to other hardware in the system. There is a mark on each valves indicating the flow direction [22].

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There are some points to consider when choosing a check valve. The most important of these criteria are connection type (flange, threaded, grooved, etc.), highest pressure and lowest separation pressure, horizontal or vertical installation direction, size, material compatibility, internal and external temperature, easy access for repair [23].

Fluid characterization has a critical role to define the check valve design parameters. CFD (computational fluid dynamics) analysing programs and simulations are often used for this purpose. CFD is a branch of fluid mechanics in which numerical methods and algorithms are used to analyse and solve fluid mechanics problems. The interactions of liquids and gases with solid surfaces are simulated with the help of computers [24,25]. The state of the results relative to the actual interaction depends on the performance of the computer or computers used. When the complex geometries, viscosity, temperature differences factors are applied to the fundamental equations of classical fluid mechanics, the solution is very difficult, even often impossible. In classical fluid mechanics, results can only be achieved in idealized simple geometries such as flat plates and pipes with circular cross-sections. CFD is required to obtain results in 99% of the remaining real problems such as lack of fluid, transition from laminar into the turbulence characteristic, deviation from the steady state condition. For this, the flow region is divided into a network of small regular elements and points simulating the basic differential equations of the flow, and the whole solution is reached step by step from these small elements with iterations [25-28].

In this article, studies on the development of a prototype, which has never been done before, that can operate at high flow loss coefficients provided by disc, which is a mechanical component used in check valves to control the flow speed, dimensions determined by analysing in computer-aided design and simulation environment and at the same time allow double-time closure with a different piston design were presented in detail. At the same time, details of the challenges addressed by the new prototype developed and how it compares with existing solutions were presented. With the prototype developed by CFD and FEA (finite element analysis), a product with increased disc strength, optimized valve weight and reduced energy losses by minimizing resistance to flow is designed. With the intensive use of simulation techniques, the competitive conditions of environmentally friendly and highly efficient valves have been improved and an innovative product has been introduced. The unique aspect of this study is that, unlike existing studies in the literature, the production and characterization of check valves were presented together using CFD analysis and simulation-supported designs with different parameters.

2. **Materials and Methods**

2.1 Design and Simulation

CFD is the design and analysis method commonly used in the valve industry. In this way, 3-dimensional flows inside the valve were simulated using various equations that describe the flow conditions. Its importance for designers is that all analyses can be carried out in a virtual environment before the prototype is produced. In this way, it will be ensured that the product can be transferred to rapid environmental conditions on the right basis the first time, with less labour and material loss. The three-dimensional designs of the products were made with the Solidworks drawing program. ANSYS computer aided simulation program was used for CFD analysis and FEA. In CFD analysis, it was solved with the K-epsilon turbulence model, and improvements were made in the boundary layers and mesh by keeping the y+ value at 3 and below. This model is the most widely used turbulence model and is mainly used for simple turbulent flows. It calculates the relationship between the kinetic energy of the fluid and the dispersed turbulent kinetic energy.

The strength values of the valve designed in FEA were determined according to the boundary conditions defined in the *EN 1074* standard. The parts were handled with two different numerical methods, singular and assembled, and interpolation solution was realized with the Rayleigh-Ritz method. It is important to consider the structural damping effects of the system in dynamic analyses. The structural damping coefficient, which is generally defined as a constant coefficient in static analyses, is defined by calculating it separately for the mass and stiffness matrices in dynamic analyses. In order to orient the mass and stiffness matrices correctly, Rayleigh damping coefficients were calculated and transferred to the system. The boundary conditions specified in the standard were applied exactly and were defined as one and a half times the nominal pressure value for the body part and ten percent more than the nominal pressure value for the disc part. With the results obtained from this stage, the material analysis and selection stage were started.

2.2 Material Selection and Justification

While modelling the body part in contact with the fluid, a body material that can withstand one and a half times the body pressure was selected regarding the analyses made according to *EN 12266* and *EN 1074* standards. The disc material that would withstand ten percent of the pressure value was selected by the same method, and the material was chosen regarding to the stresses and deformation results in the parts according to the body and disc strength analyses. Considering the FEA results, *EN GJS 400-15* (also defined as *GGG 40*) material was selected regarding to its high strength. The main reason for the high mechanical strength of *EN GJS 400-15* material was to obtain a ferritic microstructure. The carbon dissolved in the austenite phase was in the form of spherical graphite dispersed in the ferritic microstructure. The samples were produced by sand mould casting method at 1465 °C with 30% dkp steel, 30% ductile iron, and 40% runner ratio.

2.3 Sample Production and Testing

Chemical analysis of the casting material was carried out with Metavision 1008 brand spectrometer. The mechanical properties of the samples were determined by notch impact and tensile tests. The samples prepared for the notch impact test were tested with an OTTO WOLPERT WERKE PW 30/15 brand machine located in the R&D Center at a temperature of 25 °C, and the samples prepared for the tensile test were tested at room temperature with an OTTO WOLPERT U-40 type tensile device. The main reason for choosing this equipment was that they enable precise measurements to be made easily.

2.4 Microstructural Analysis

The samples, which were fixed into polyester moulds for microstructural analysis, were grinded and polished with the STRUERS Tegrapol-21 brand grinding and polishing device by turning 90° each time with 600 grades SiC sandpaper, 220 grade 9 µm, 3 µm and 1 µm felt and diamond pastes, respectively, and made ready for the etching process. Prepared samples for the microstructure analyses were etched with 3% Nital solution. The samples were investigated with a 1000 magnification NIKON ECLIPSE LV 150 optical microscope. The hardness values were tested at room temperature with an ALBERT GNEHM brand universal hardness measuring machine with Brinell tip. It was possible to conduct more detailed research with these devices.

2.5 Hydrodynamic Tests

The hydrodynamic tests of the produced body and mounted disc were carried out according to EN 1074 standard. Regarding to the definition of this standard, pressure tests were evaluated for the body under 16 bar pressure without showing the leakage and damage on the valve. The reason to choose this procedure was to evaluate the hydrodynamic behaviour of the check valves on the tough environment.

3. Results and Discussion

One of the most important steps in performing CFD analyses properly is to define and handle the data correctly, and more detailed data about the line and fluid is needed. Therefore, the technical details targeted in the article for the CFD analyses in line with the requirements defined in the *EN 1267* and *EN 1074* standards are given in Table 1.

The parameter that would support the velocity vector analysis of this system should be its characteristic behaviour under 16 bar pressure, and velocity vector analysis was carried out. Accordingly, when the disc was in the fully open position, the resistance of the disc and the body against flow could be characterized more clearly. Innovative design trials have been carried out to suit the desired conditions. Figure 1 shows the velocity vector analysis of the system under 5 m/s. According to the research in the literature, it has been determined that there are factors that disrupt laminar flows, sharp surface change, temperature change and material resistance in valve disc materials [29-31]. As a result of these evaluations, the methodology proved effective in the CFD analysis of the disc material at a flow rate of 5 m/s, and it was observed that the flow lines were suitable in green colour.

Table 1. Technical properties of the design inputs

Line Pressure (Bar)	16
Fluid Velocity (m/s)	5.0
Flow Coefficient (m^3/h)	52000

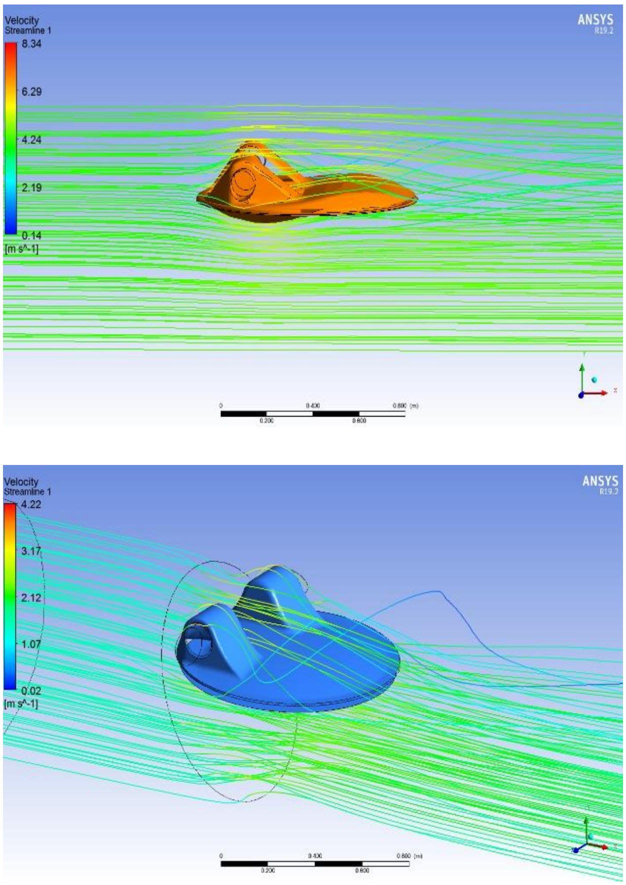


Figure 1. Velocity vector analyses of the design for front (upper) and isometric (below) views

In order to increase the desired flow coefficient, in other words, the valve efficiency, various designs have been made in the disc geometry. The mechanical numerical analysis method was carried out by defining the boundary condition of ten percent of the nominal pressure for the disc materials, which were carried out by considering the yield strength values of 240 MPa. Accordingly, the mechanical analysis of the disc regarding to 18 bar, which corresponds to 1.1 times the maximum working pressure of 16 bar, is shown in Figure 2. The design developed to increase the mechanical strength of the disc exposed to the flow surface was defined by FEA and no red areas, which represent high stress zone encouraging plastic deformation, were observed.

The assembly of body, disc, and shaft materials by using the Solidworks design program and simulations by the help of ANSYS FEA are shown in Figure 3. In this Figure (a) represents the body, disc, and shaft assembly. (b) expresses disc material's and (c) expresses shaft material's mechanical strength by FEA analysis. The most important issue here would be that no plastic deformation was observed in the designs. While elastic deformation regions are defined in green, high plastic deformation is observed in the regions defined in red. In this case, the material will exhibit irreversible defects and will dangerously fail in application. According to the results obtained, the absence of red areas indicates that there was no plastic deformation in all of the components, and the results achieved were satisfactory.

The final version of the solid models of the designs before casting was realized with the help of Solidworks drawing program and the final version was decided (Figure 4). The most important advantage of this stage is to show that 3D designs of products can be made on a component basis according to exact measurements. This allows designers to quickly make final revisions of the product before the prototype goes into production.

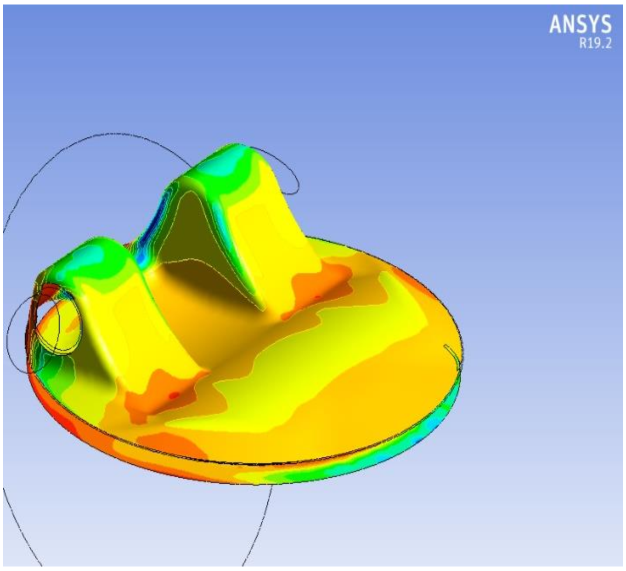
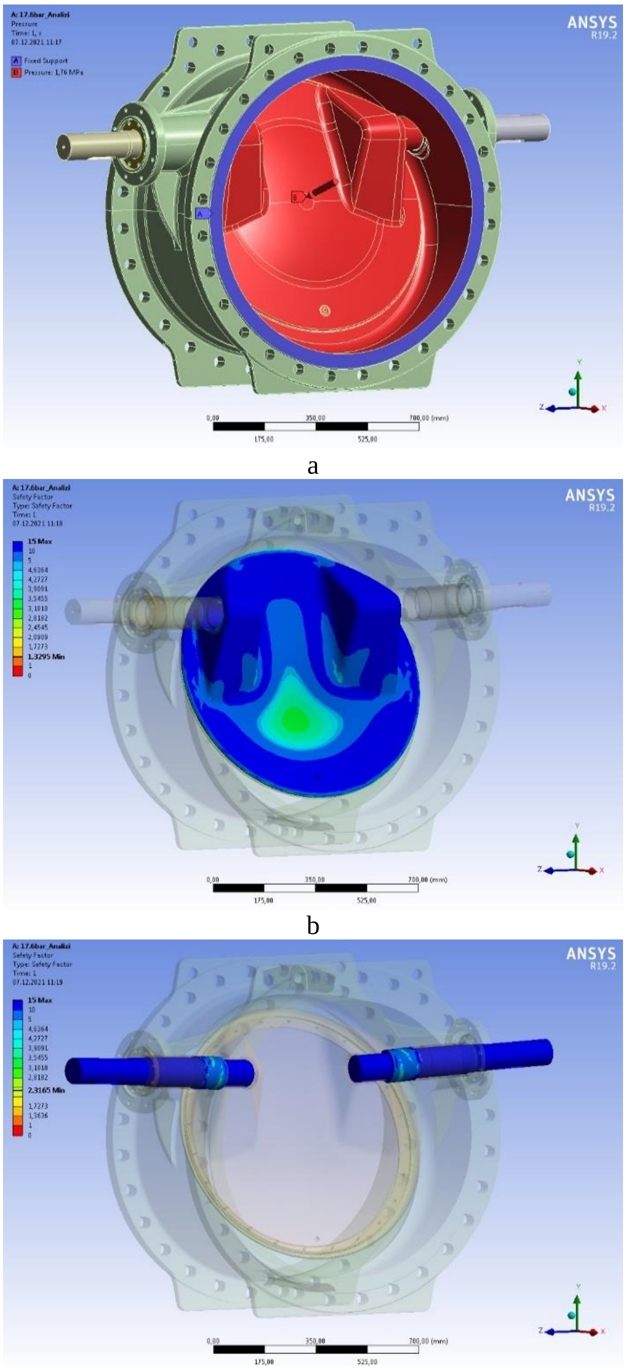


Figure 2. Mechanical strength definition by FEA



a

b

c

Figure 3. Assembled body, disc, and shaft's FEA analysis

The casting models of the disc and body materials, which were designed by analysing their hydrodynamic properties, and the production of the core box were carried out on CNC machines with CAM software. The wooden models' productions of the valve components are shown in Figure 5. The use of CAD-CAM applications gives accurate results when used for CNC milling. This results in a significant increase in accuracy. In this sense, it greatly increases control over the production process. Using CAD-CAM engineering helps save time at every stage, meaning prototypes and finished products can be produced much faster. Improved accuracy and time savings also have an important benefit today: It reduces costs.

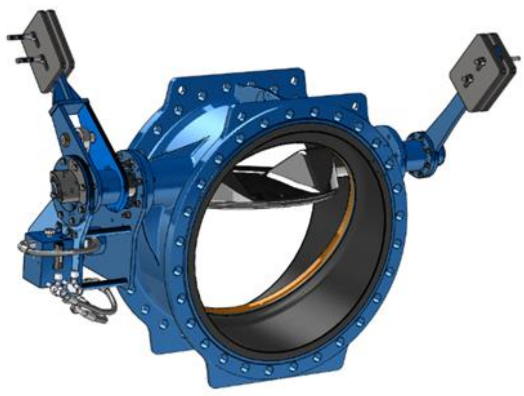


Figure 4. Final version design made by Solidworks

Figure 5. Pre-cast preparations of components' material

The four main factors controlling the microstructure in cast irons are carbon content, alloying element, solidification during and after solidification cooling rate and after casting heat treatments. What makes these stages important are carbon and phosphorus analyse with manganese and silicon values. The final chemical of the parts that were the subject of the study analysis values are shown in Table 2. As can be seen in the chemical composition, ferrite levels of the building elements perlite phase in the structure affects the amount of formation. Obtaining a completely pearlitic structure, the silicon content must be low, where the manganese rate has to be high. However, since there was no need for a full pearlitic structure in this study, cast iron products containing 2-4% carbon, 0.4-3% silicon, 0.4 - 0.8% manganese and 0.1 - 0.8% phosphorus were preferred. This also fulfilled the requirement of the general used cast iron products.

Microstructure, hardness, shrinkage over the cast part obtained after the applications of the production processes strength, % elongation, notch impact tests were performed. These tests were taken from the cast part itself applied to the samples. Figure 6 shows the microstructure images. According to the literature, it was expected to have a high ferrite content and a homogeneous distribution of sphericity. Regarding to the etched microstructure image with homogeneously distributed graphite with 45% ferrite was obtained [32,33].

Considering the literature research and standard scans, it is appropriate that the yield strength of the product is 200 N/mm^2 and the tensile strength is 300 N/mm^2. As a result of this study, 250 N/mm^2 yield strength and 400 N/mm^2 tensile strength were obtained and ideal conditions were provided. On the other hand, micro hardness values should be 130-175 HB and Charpy impact test values must be minimum 12 Joule at the room temperature. As the mechanical test results given in the Table 3, it was observed that the mechanical values fulfilled the requirements of the standards [34,35].

The visual of the prototype production, which has been casted, assembled, and ready for the hydrodynamic test, is given in the Figure 7. When the water flow starts, the check valve flap is pushed by the pushing force of the water and continues its flow towards the direction of the water flow. When the water flow stops, the valve starts to close. The check valve closes with the help of the weight attached to the flap shaft and the pushing force of the returning water. It prevents water from returning to the floodplain or flow line. It has been observed that the design carried out in the solid model and the prototype production exactly overlap.

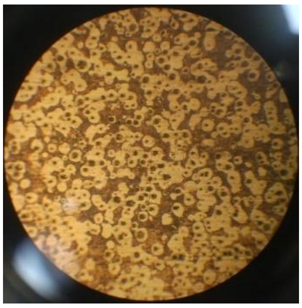


Figure 6. Casting material etched microstructure image

Table 2. The mechanical analyses of the disc, body, and shaft materials

Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)	Hardness (HB)	Charpy (Joule)	Structure
250	400	18	150	23	Ferritic

Figure 7. Prototype production of the developed design

Figure 8. Hydrodynamic test equipment

The pressure tests of the produced body and the assembled disc were carried out according to defined standard conditions. Materials in contact with water intended for human consumption must comply with the requirements of national regulations in the country of use and must not affect the water in any way. This means that the chemistry and physical appearance of the water should not change after contact with a valve – you should not see, smell, feel or taste any difference in the water. Additionally, all interior and exterior materials must be resistant to corrosion or protected by appropriate means. Pressure tests were evaluated for the body under a pressure of 16 bar without the leakage and damage on the valve. The design in which the pressure test was performed is given in the Figure 8.

4. Conclusions

As a result of the analyses, simulations, prototype production and hydrostatic tests, a unique check valve article was presented for the first time in the industry. The project has been a guide in improving and developing the product geometry for the final goal, with various and repetitive applications on flow analysis. At the same time, it has been satisfactory that the needs can be met with the mechanical auxiliary equipment applied. With this completed project, R&D capability for the design of variant products has been increased and national and international patent applications have been made for the curved body and stepped shaft of the product that is the output of this project. Regarding this design, R&D Innovation Project has also been successfully concluded.

As a result of simulation analyses in products designed for use in fluid lines, no turbulent flow was observed at a flow rate of 5 m/s and an ideal laminar flow was determined. These results were validated by hydrostatic tests and verified by leak tests.

Simulation studies were carried out in such a way that the fluid coefficient was 52000 m^3/hour when the valve was in the fully open position under 16 bar pressure and 5 m/s fluid velocity, which were fulfilled the requirements of the *EN 1267* and *EN 1074* standards.

No defects were detected in the casting of the valve components and 45% ferritic structure was obtained. In the ferritic structure, it takes time for all the carbon dissolved in the austenite to turn into spherical graphite required. This microstructure of the material consists of randomly dispersed spherical graphite, which causes high impact strength, high hardness, and convenient tensile test results. The casted components were showed twice Charpy impact strength resistance than required and met the tensile-hardness tests standards requirements.

In final summary, the check valve with %45 ferritic structure, resistant to the 52000 m^3/hour fluid coefficient, exposed to the flow tests with 5 m/s fluid velocity was designed successfully. The acceptance tests were carried out according to a minimum yield strength of 240 N/mm^2 in the body design, no adverse events were detected under 16 bar and no plastic deformation occurred in the product under 24 bar pressure.

This research serves as a guide for improving product geometry through flow analysis. It has been satisfactory that the needs can be met with the applied mechanical auxiliary equipment. It has increased its R&D capability for similar products to be produced. The product that is the subject of the article is a design, which has the potential for commercialization, as it will increase the manufacturability of the companies and then the same or similar ones can be made within the needs.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

Erhan Ozkan developed the methodology, performed the analysis, and wrote the manuscript.

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