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CAD SUPPORTIVE IN DESIGN OF MULTICHANNEL PIPE FOR AUTOMOTIVE APPLICATION

Key words: CAD application for shape and dimension design, multichannel pipe, numerical analysis, strength test, fluid mechanics, heat transfer.

Abstract: It is necessary to carry out investigations on device behaviour before it will work in real conditions. Helpful tools are CAD systems and numerical simulations on virtual geometric models. They allow relatively cheap and fast analysis of devices without using expensive real models. This paper presents a method of multichannel pipe design with the help of a CAD system in terms of its strength and working conditions as an internal heat exchanger with carbon dioxide as a refrigerant. Two aluminium alloys were chosen: AA 3103-H112 and AA 6060-T6, and several shapes of channels. Results show that the selection of proper materials is one of the most important stages. It affects the strength of the pipe. A second significant parameter is the shape of external channels. It has been shown that it is important to choose proper value of radius R1 (corner between upper area of external channel and lateral surface of external channel). For the analysed type of multichannel pipe, the most appropriate value of radius R1 was 1 mm. As for heat exchange between fluids in internal and external channels, an important parameter was the thickness of the wall between the mentioned channels. It has been demonstrated that heat exchange efficiency depends on wall thickness and on the way of achieving this.

Wspomaganie CAD przy projektowaniu rur wielokanałowych do zastosowań motoryzacyjnych

Słowa kluczowe: zastosowanie CAD w doborze kształtu i wymiarów, rura wielokanałowa, analiza numeryczna, test wytrzymałościowy, mechanika płynów, transfer ciepła.

Streszczenie: Często konieczne jest przeprowadzenie badania zachowania się urządzenia zanim będzie pracowało w warunkach rzeczywistych. Jednym z przydatnych narzędzi to umożliwiających są systemy CAD oraz symulacje numeryczne przeprowadzane na wirtualnych modelach geometrycznych. Pozwalają one na dokonanie stosunkowo taniej i szybkiej analizy urządzenia bez konieczności użycia kosztownych modeli rzeczywistych. W artykule przedstawiono metodę projektowania rury wielokanałowej przy pomocy systemów CAD pod kątem ich wytrzymałości i warunków pracy jako wewnętrznego wymiennika ciepła z dwutlenkiem węgla, pełniącym rolę czynnika chłodniczego. Do analizy wybrano dwa stopy aluminium: 3103-H112 i 6060-T6 oraz kilka różnych kształtów kanałów. Wyniki pokazały, że dobór odpowiednich materiałów jest jednym z najważniejszych etapów projektowania rur. Ma to wpływ na wytrzymałość rury. Drugim istotnym parametrem jest kształt kanałów zewnętrznych. Wykazano, że dobór odpowiedniej wartości promienia R1 (narożnik pomiędzy górną i boczną powierzchnią kanału zewnętrznego) jest istotny. Dla analizowanego typu rury wielokanałowej wartość promienia R1 równa 1 mm była najbardziej właściwa. W przypadku wymiany ciepła pomiędzy płynami w kanałach zewnętrznych i wewnętrznym ważnym parametrem była grubość ścianki pomiędzy wymienionymi kanałami. Wykazano, że efektywność wymiany ciepła zależy od grubości ścianki oraz od sposobu osiągnięcia jej zmiany.

Introduction

The investigation of device performance is one of the most important stages in a device design project. This can be provided both by physical experiments on test models and numerical investigations by using suitable software and numerical model. That later method allows having a relatively fast and cheap analysis of each component and the device as a whole without the need for using arduous methods like photoelasticity or viscoplasticity. Moreover, when using proper numerical models, the results obtained by physical and numerical investigations are close to each other [1, 2]. This allows one to predict the level of processes forces, stress and strain patterns in elements, and heat transfer in components and devices. Thus, the application of numerical methods has wide range in technology and industry. Roy at. all [3] developed a numerical simulation as a replacement for real tests of full corroded pipes strength. Furthermore, they used it to investigate the effects of several parameters on failures of pipes with good comparisons to the results of physical tests. Similar tests were presented in [4], where the authors conducted a numerical investigation of local corrosion influence on the strength of members under compressive loads. On the other hand, in work [5], the authors used FEM to clarify the deformation, stresses and strain in areas where defects, like fractures caused by burst, occurred. These test indicated that time-consuming tests on real models and elements may be replaced by numerical investigation. When this type of analysis is conducted, it is important to select the most proper calculation method, model describing material, geometry, and physical aspects of the process.

Presently, numerical investigation is used widely in computational fluid dynamics and heat exchange analysis. Using Navier-Stockes or Reynolds equations and Finite Element Method (FEM) or Finite Volume Method (FVM), it is possible to describe and show internal or external fluid flow. This is especially important when flow of real fluids is investigated and/or turbulent flow may occur. Many researchers conducted experimental and numerical analysis in this field. The influence of pipe curvature [6, 7], wall roughness [8–10], and changes in the pipes' cross-sections [11] on the flow of fluids and pressure drops were investigated. It shows the importance of this type of study. It is also important to choose proper mathematical models, especially for describing turbulent flow. In the case of flow through channels of pipes, most commonly used turbulent models are k-ε and k-ω [6, 7, 12], due to relatively easy solving of turbulence equations.

Besides the description of fluid flows in the case of multichannel pipes, numerical methods, like FEM and FVM, are also used to calculate the level of heat exchange between fluids. Hesham in [13] compared results obtained by two methods: experimental and CFD investigation. It was shown that values of the heat transfer coefficient calculated from experimental data and provided by numerical analysis were similar. Thus, in the case of relatively simple shapes of pipes, numerical investigation is sufficient to calculate temperature change, pressure drops, and the values of the velocity of fluids in each channel of multichannel pipes.

In this paper, numerical investigation of multichannel pipes behaviour was carried out using Finite Element and Finite Volume Methods. Several parameters, like the shape of channels and flow conditions, have been varied to study their effects on the performance of proposed models of pipes.

1. Material and method

The numerical investigation of multichannel pipe behaviour consisted strength test of the proposed geometrical model, fluid flow simulation, and the simulation of heat transfer between fluids. Simulations were carried out using SolidWorks Simulation in the case of strength test, and Solid Works Flow Simulation for fluid flow and heat transfer investigations. In the case of pipe strength, the general assumption was made that the value of stress in a pipe should not excide the value of material yield strength under a given pressure. As a material model, an isotropic model was chosen. As a material of pipe, two commonly used aluminium alloys in the automotive industry were selected: AA 3103 H112 and AA 6060 T6. Their properties are shown in Table 1. In the case of the fluid, R744 refrigerant (carbon dioxide) was selected as one of proposed substitutions for R134a.

Table 1. Properties of selected aluminium alloys

Material	Elastic modulus, MPa	Poisson ratio *v*	Yield strength, MPa	Ultimate tensile strength, MPa
AA 3103 H112	70000	0.33	35	95
AA 6060 T6	69500	0.33	150	190

To determine the strength of multichannel pipe, two values of pressure were selected. In the case of the internal channel, the value of pressure was equal to 32 MPa; whereas, for external channels, the value of pressure was 26 MPa (Fig. 1). Those values were established on the basis of information obtained from Maflow Poland about the conditions of real pressure tests, where the refrigerant is a carbon dioxide (R744) in a transcritical state. They correspond to the instantaneous pressure jumps in each channel, which can appear in the refrigeration system, mostly when it is started, and are higher than pressure values in normal working conditions. Withstanding them by a multichannel pipe ensures its proper operation. This test simulation allows one to select the most appropriate geometrical model of multichannel pipe and tell which of the investigated materials can be used. The procedure of test is shown in Figure 2. The values of pressure in strength test are higher than in the case of working conditions for carbon dioxide as a refrigerant.

Fig. 1. Pressure in multichannel pipe during strength test

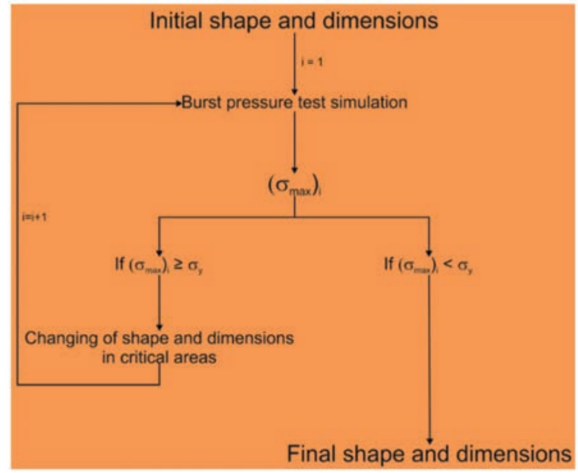

Fig. 2. Procedure of strength test of multichannel pipe under pressure

As a result of this test, the value of maximum effective stress in the multichannel pipe σ_{max} was obtained, calculated according to von Misses equation. By comparing this value with yield strength σ_y of the applied material, it could be determined if shape and dimensions used to build geometrical model of multichannel pipe were adequate. If yield strength was exceeded, then

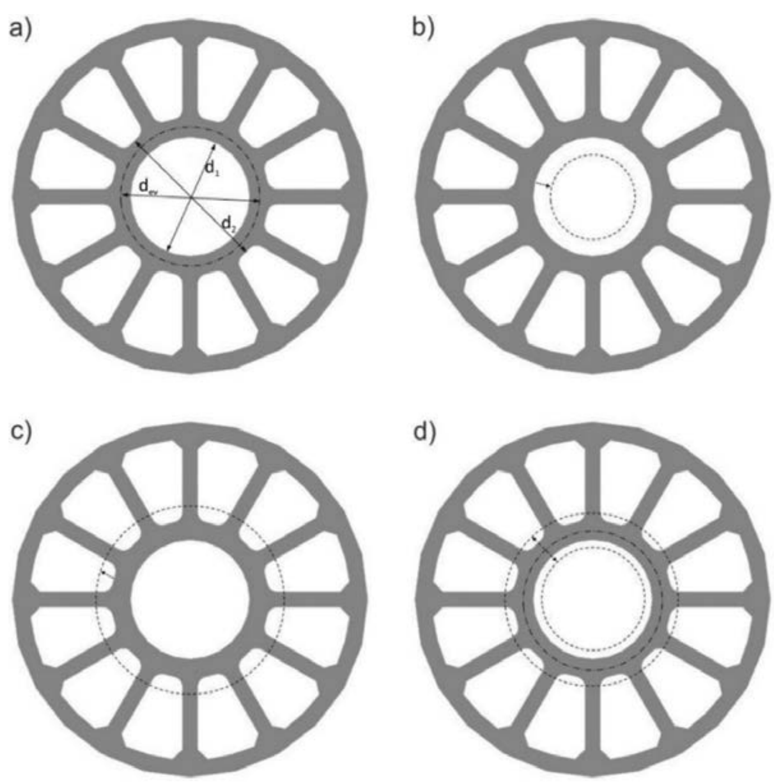

Fig. 3. Cross-section of multichannel pipe with the markings of internal and external diameters of internal channel (a) and methods of wall thickness change by decreasing of d_1 (b), increasing d_2 (c) and simultaneous decreasing of d_1 and increasing of d_2 (d); d_1 – internal diameter, d_2 – external diameter, d_{ev} – median diameter

changes in pipe geometry were necessary. Especially, this had to be carried out in locations of stress and strain. Thus, the next step consisted in building a graph of stress and strain distributions in the pipe and analysing critical areas. It determined which parts of geometrical model needed to be changed by changing its shape and/or dimensions. Afterwards, new a geometrical model of the pipe could be re-tested, the maximum stress could be calculated and compared to the assumed limit stress. It was repeated until the conditions of the tests were met.

Geometrical models of multichannel pipes were built using SolidWorks software. As a design of multichannel pipe, we only took into consideration pipe with one internal channel and eleven external channels. Furthermore, the shape of internal channel was not changed and the outer diameter of pipe was set up as a constant equal to 18 mm. Changes included increasing and decreasing of internal diameter d_1 and external diameter d_2 of the internal channel (Fig. 3) and slight changes in the external channels shape with little changes in dimensions (Fig. 4). Except for the rounded upper corners R_1, the external channel's strength with chamfered corners was investigated (Fig. 4b). Ranges of investigated parameters are shown in Table 2.

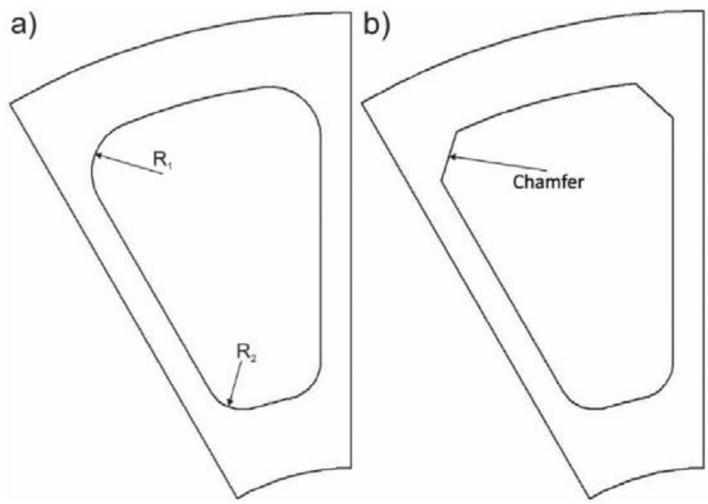

Fig. 4. Shapes of external channels: rounded upper corner (a) and chamfered upper corner (b)

Table 2. Ranges of investigated parameters of multichannel pipe geometry

Parameter	Values, mm
R_1	0.45–1.00
R_2	0.25–1.00
d_1	5–7
d_2	7–9

One of the applications of multichannel pipes can be heat exchangers. Thus, besides strength test, it is necessary to investigate the ratio of heat exchange between fluids flowing through channels in terms of shape and dimensions. Appropriate selection of these parameters can improve the efficiency of the device.

The procedure of fluid flow test simulation consisted in the calculation of temperature, pressure drop of the fluid in respective channels, and the determination of heat transfer effectiveness. First, an appropriate geometrical model and material has to be selected. The main assumption was that both geometry and material had to pass strength test. Then, simulation of fluid flow and heat exchange was carried out using software – SolidWorks Flow Simulation.

To carry out simulations, initial and boundary conditions have been established for both internal and external channels. The initial conditions included the following: initial temperature of hot and cold gases, and its initial pressure and fluid flow rates expressed as mass flow of mediums (Table 3). In the case of boundary conditions, Fourier boundary conditions were selected for heat exchange between the outer wall of the pipe and the environment. Thus, it was assumed that environmental temperature was equal to 298 K and convective heat-transfer coefficient was 25 $Wm^{-2}K^{-1}$.

The calculated initial value of the Reynold's number for both internal and external channels were much above 4000. Thus, full turbulent flow of fluids was selected. As a model of turbulent flow, k-ε was chosen. In the case of fluid flow, counter flow, as the most efficient type of flow in an internal heat exchanger, was set up (Fig. 5).

Table 3. Initial conditions of fluid flow through each channels

Mass flow, kg/h	Hot gas (high pressure)		Cold gas (low pressure)	
	Tempe-rature, °C	Pressure, MPa	Tempe-rature, °C	Pressure, MPa
100	60	12	13	4.5

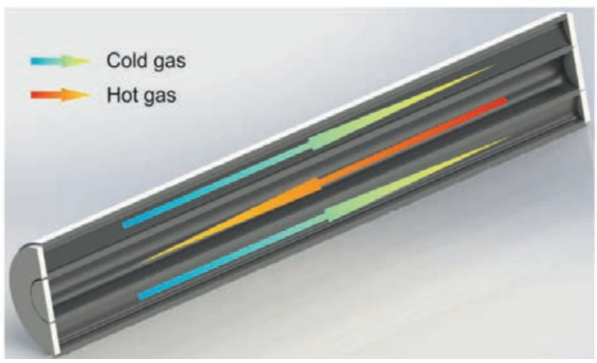

Fig. 5. Fluid flow in multichannel pipe

Results of numerical calculations allowed the determination of values of pressure drops and temperature changes in each channel for the whole range of proposed geometrical models of multichannel pipes. Furthermore, the effectiveness of heat exchanger for the counter flow of fluid, given by Equation 1, was predicted.

$$\varepsilon = \frac{q}{q_{\max}} = \frac{1-\exp\left[-\left(1-\frac{1}{R}\right)S\right]}{1-\frac{1}{R}\exp\left[-\left(1-\frac{1}{R}\right)S\right]} \quad (1)$$

where

$$R = \frac{\left(\dot{m}c_p\right)_{cold}}{\left(\dot{m}c_p\right)_{hot}} = \frac{T_{hot}^{in} - T_{hot}^{out}}{T_{cold}^{out} - T_{cold}^{in}}$$

$$\text{and} \quad S = \frac{kA}{\left(\dot{m}c_p\right)_{cold}} \quad (2)$$

In Equations 1 and 2, the following symbols were used: $\dot{m}$ – mass flow of flowing fluid, c_p – specific capacity, T_i^{in}, T_i^{out} – temperatures on the entry and exit of respective (hot or cold fluid) channels, k – heat transfer coefficient, and A – heat transfer area.

2. Results and Discussion

2.1. Multichannel pipe strength

First, the influence of upper corner shape and dimension of the external channel on pressure resistance was investigated. As expected, the pipe with a chamfered shape of the upper corner was characterized by the highest value of maximum stress in the pipe in both cases of applied materials (Fig. 6). However, in the case of 3103 aluminium alloy, the maximum stress in the pipe was much higher compared to its yield strength and ultimate tensile strength (Fig. 6a). Even changing from a chamfered upper corner to a rounded corner and, simultaneously, increasing the value of corner radius, did not significantly decreased value of maximum stress. Furthermore, the area of occurrence of dangerous stress did not considerably decreased (Fig. 7 – yellow and red areas).

In the case of 6060 aluminium alloy, it was found, that increasing the value of the upper corner radius has caused the same level of decreasing the maximum stress value as for 3103 material (Fig. 6b). However, the value of maximum stress in the pipe for 6060 alloy decreased below the value of ultimate strength of this material. Moreover, localization of stress in the pipe occurred only for chamfered and rounded shapes with R_1 = 0.45 mm corner cases (Fig. 8a, b). For others, the area of dangerous stress occurrence was smoother (Figs. 8c, d). Moreover, values of maximum stress for both cases of the upper corner radius value were similar. Thus, in subsequent studies, only 6060 aluminium alloy and values of corner radius R_1 equal to 0.674 mm and 1 mm were taken into account.

An increase in the value of the radius of upper corners in external channels did not cause a decrease in the maximum stress in the pipe under yield strength of the selected material (6060 aluminium alloy). Thus, it was necessary to change the geometry of pipe channels in critical areas – bottom corners of external channels. The second option was to change the aluminium alloy to a material with higher mechanical properties.

Changes in geometry were made separately by decreasing and increasing the bottom corners' radii R_2 and by increasing and decreasing of internal d_1 and/or external d_2 diameters of internal channel. In the first case, values of R_2 were from 0.25 mm to 1 mm. As a result, it turned out that changing of bottom corners radius did not significantly decrease the maximum stress value in the pipe. Furthermore, for both R_2 equal to 0.25 mm and 1 mm, the value of maximum stress was higher than the ultimate tensile strength of 6060 aluminium alloy (Fig. 9). Thus, this type of geometry improvement method was not correct in the case of multichannel pipe strength.

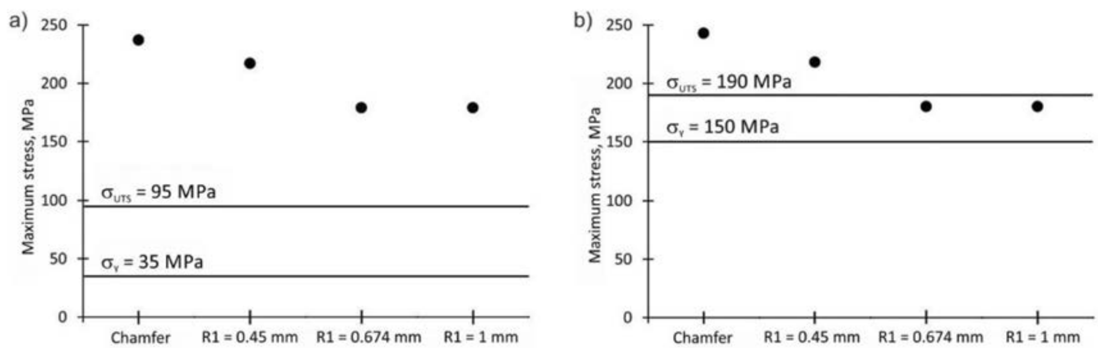

Fig. 6. Influence of upper corner shape and dimension on value of maximum stress in the case of 3103 (a) and 6060 (b) aluminium alloy

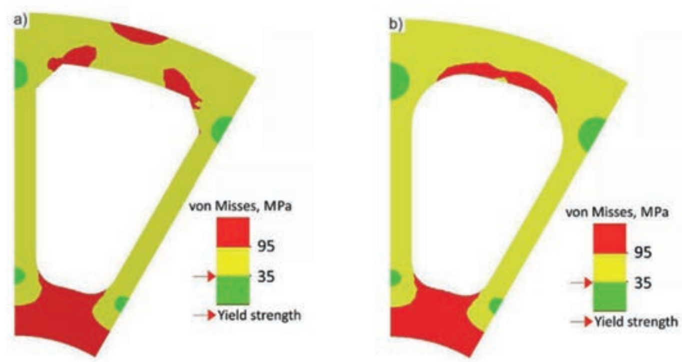

Fig. 7. Stress distribution in pipe made from AA 3103: chamfered (a) and rounded with R_1 = 1 mm (b) upper corner

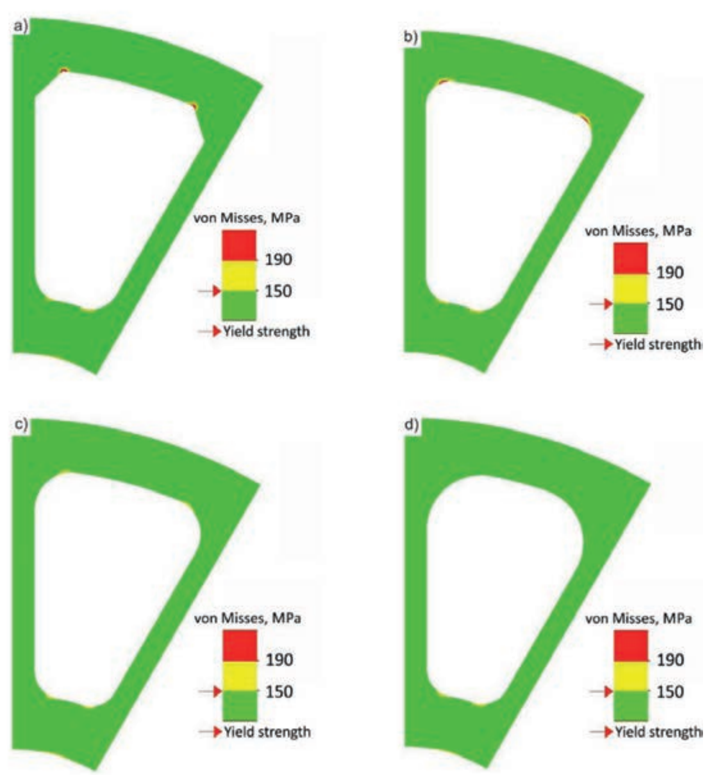

Fig. 8. Stress distribution in pipe made from AA 6060 with corner: chamfered (a) and rounded with R_1 = 0.45 mm (b), R_1 = 0.674 mm (c) and R_1 = 1 mm (d)

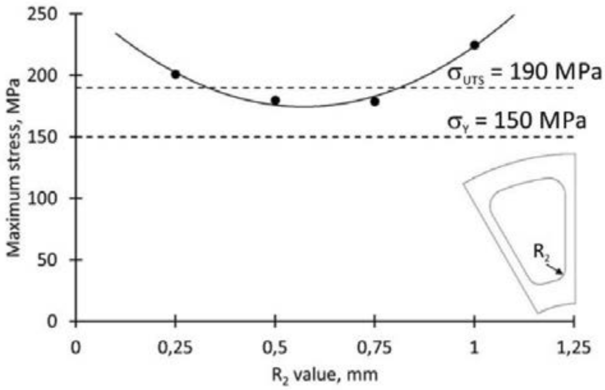

Fig. 9. Maximum stress dependence on bottom corners radius value

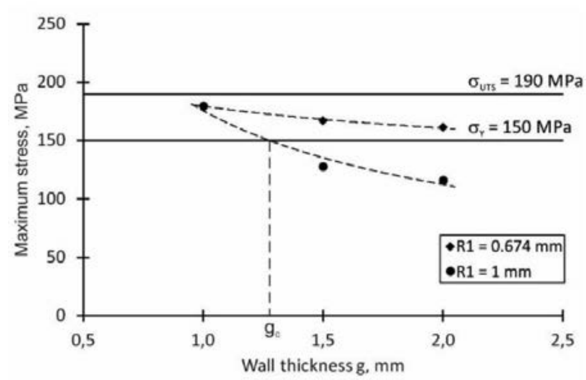

Fig. 10. Maximum stress dependence on wall thickness between internal and external channels for upper corner radius value equal to 0.674 mm and 1 mm

The second method of pipe geometry changing consisted in increasing the wall thickness between internal and external channels (from 1 mm to 2 mm). It was made by the following changes:

- Decreasing d_1 with d_2 constant (Fig. 3b),
- Increasing d_2 with d_1 constant (Fig. 3c), and
- Simultaneous increasing d_2 and decreasing d_1 (Fig. 3d).

Results show that the increase of wall thickness between internal and external channels allowed a reduction in the maximum stress value in the pipe (Fig 10). In the case of R_1 equal to 0.674 mm, the reduction was significantly smaller than for R_1 = 1 mm. Moreover, for the latter, the value of maximum stress in the pipe dropped below 150 MPa for wall thicknesses equal to 1.5 mm and 2 mm. The calculated value of critical thickness g_c – above which maximum stress in pipe was lower than material yield strength – for R_1 equal to 1 mm was about 1.3 mm, when for R_1 = 0.674, it was almost three times higher. Thus, the usage of an upper corner radius value equal to 1 mm connected with wall thickness higher than 1.3 mm (for example g = 1.5 mm) should be sufficient to achieve the maximum stress value in the pipe below the yield strength of 6060-T6 aluminium alloy, and it should not allow damage to the multichannel pipe during pressure tests.

2.2. Fluid flow simulation

During fluid flow simulation, the geometrical model with rounded upper corners in external channel was used. Its value was set up to 1 mm. As for wall thickness, the range from 1 mm to 2 mm was taken into account. During simulation, the influence of several parameters, such as wall thickness and length of pipe, on pressure drop and temperature change in each channel was investigated.

2.2.1. Wall thickness influence

In this paper, the change of fluid temperature and its pressure drop were calculated as a difference between their initial values and calculated values on the exit of each channel. The graphs of wall thickness influence shows that an increase in wall thickness also increases the level of temperature change in channels (Fig. 11). Moreover, the results show the importance of wall thickness change in method selection. In the case of d_1 constant and d_2 variable, the increase of temperature change relative to wall thickness was very low. On the other hand, when d_1 was decreasing and d_2 was constant, for internal and external channels, the level of *DT* was the highest. A similar dependency was shown in terms of the heat exchange effectiveness (Fig. 12).

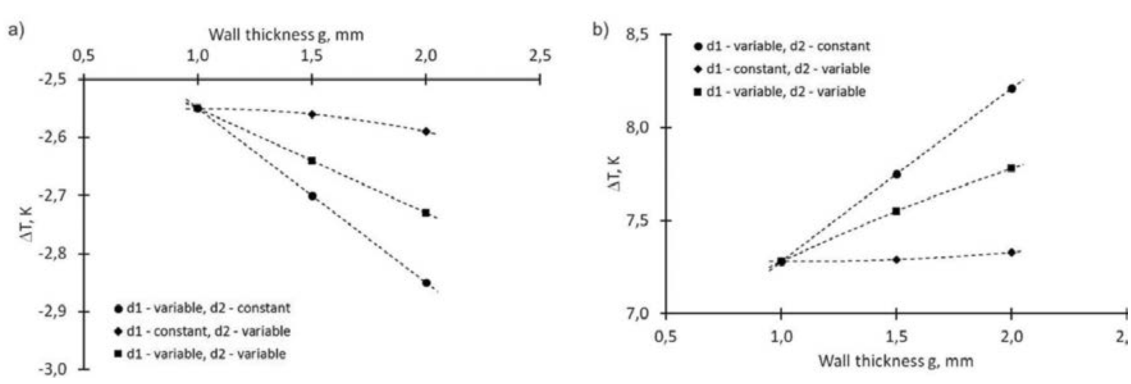

Fig. 11. Temperature change as a function of wall thickness for respective channels: (a) internal, (b) external

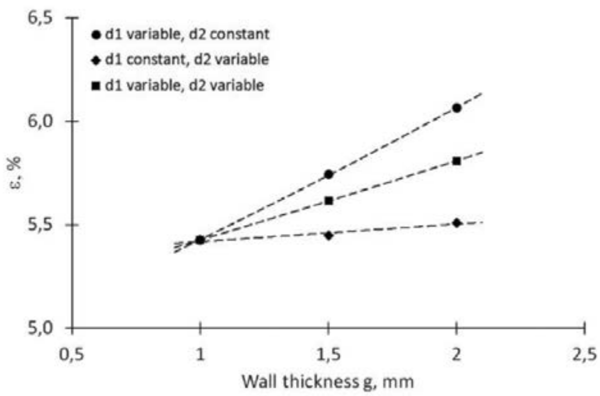

Fig. 12. Effectiveness of heat exchange as a function of wall thickness

However, it was shown that the increase in wall thickness can cause an increase of pressure drop in pipes channels (Fig. 13). In terms of compressor and expansion device performance, this situation can be unfavourable. Thus, it is necessary to choose the most appropriate value of wall thickness, which, on the one hand, gives the highest heat exchange between fluids flowing through internal and external channels, and on the other hand, will not cause a significant increase of pressure drop. Furthermore, the type of wall thickness change is also very important. In the case of d_1 variable and d_2 constant, pressure was almost constant for external channels. However, its values in internal channel change substantially. In the case of d_1 constant and d_2 variable, the situation was the other way around.

On the other hand, when d_1 and d_2 are variable, the pressure drop of fluid increased in both channels (internal and external). However, compared to previously mentioned cases, this increase was lower than in the case of d_2 (for internal channel) or d_1 (for external channels) constant (Fig. 14). Furthermore, the value of temperature change and heat exchange effectiveness for this case is higher than for d_1 constant and d_2 variable.

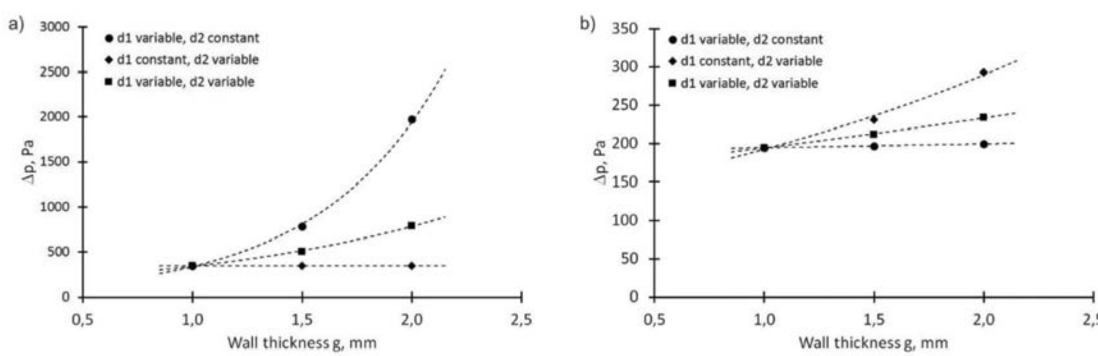

Fig. 13. Pressure drop as a function of wall thickness for respective channels: (a) internal, (b) external

2.2.2. Pipe length influence

Except for the wall thickness between internal and external channels, pipe length *L* can also affect the level of temperature change, heat exchange effectiveness, and pressure drop. Theoretically, the longer the pipe, the higher is the ratio of heat exchange and temperature change should occur. The results of simulation have shown that this assumption was correct (Figs. 14, 15).

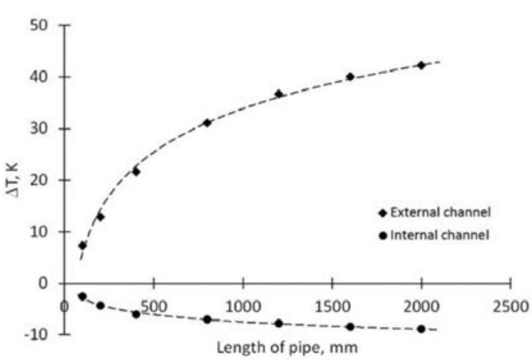

Fig. 14. Temperature changes as a function of pipe length

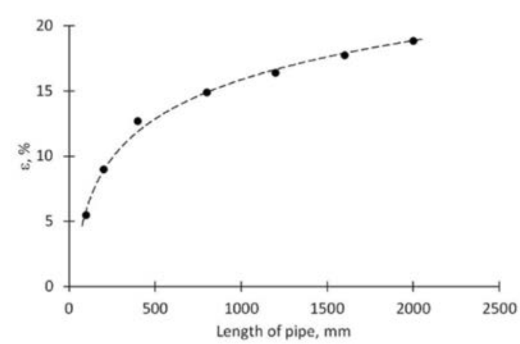

Fig. 15. Heat exchange efficiency as a function of pipe length

However, after the critical value of pipe length, its influence on those parameters was getting smaller with the lengthening of pipe. The most significant ratio of fluid temperature change and heat exchange efficiency increase was for value of pipe length not greater than

800 mm. For pipe length equal to 2000 mm, the increase of heat exchange efficiency, relative to 800 mm, was only about 25%. At the same time, the pressure drop ratio increased significantly from about 0.2 MPa for L = 100 mm to about 4 MPa for a pipe length equal to 2000 mm (Fig. 16). In the case of L = 800 mm, the calculated pressure drop was about 1.6 MPa.

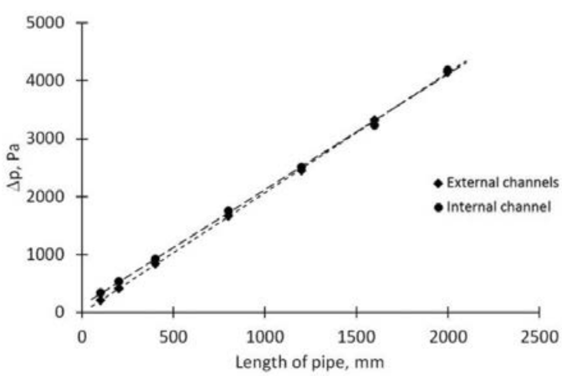

Fig. 16. Pressure drop as a function of pipe length

Conclusion

The procedure of multichannel pipe design with CAD system support was presented. During numerical tests, several parameters were taken into account: material, shape, and the dimension of channels. An appropriate combination of these parameters allow one to choose the most applicable geometry of a multichannel pipe in terms of its strength, heat exchange efficiency, and ratio of pressure drop. For further reference, several conclusions were made:

- In the case of R740 refrigerant usage of aluminium alloys is limited to alloys with high strength. Between two presented materials (AA 3031-H112, AA 6060-T6) only 6060-T6 could be used in subsequent tests, provided that some changes in geometrical shape of pipe occur. In the case of 3031-H112 mechanical properties of material were too small.
- Results of simulations have shown that the value of the upper corner radius of rounding R_1 and wall thickness between internal and external channel g have an influence on the value of maximum stress in the presented multichannel pipe. With the right choice of both parameters, the value of maximum stress in the pipe can decrease below of yield strength of pipe material. In the case of 6060-T6 aluminium alloy, the values of those parameters should be at least 1 mm and 1.3 mm, respectively.
- In the case of proposed multichannel pipe, numerical investigation has shown that wall thickness between internal and external channels and pipe length affected heat exchange between hot and cold fluids and pressure drop. Furthermore, the selection of a method by which the increase of wall thickness was achieved played an important role in the quantity of obtained results. In terms of fluid temperature change and the effectiveness of heat exchange, the smallest increase was calculated in the case when d_1 was constant and d_2 was variable. On the other hand, an increase of d_1 (on the assumption that d_2 = cons.) caused a significant increase in both calculated variables. A similar situation occurred in the case of pressure drop. Except that, depending on the channel (internal, external), the given parameter had a different effect on pressure drop in the fluid.
- For presented type of multichannel pipe, it has been shown that the selection of wall thickness equal to 1.5 mm and pipe length about 800 mm gives good results in terms of heat exchange efficiency and pressure drop.

The presented method is the first stage of multichannel pipe design that allows one to check the assumptions about the geometry of pipes. The obtained results may help to optimize the shape of multichannel pipes in relation to their strength, flow of refrigerant, and heat exchange between fluids in pipe. Further research on physical objects is necessary to validate the appropriateness of selected materials and geometric parameters.

Acknowledgements

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