Intermediate Master Project – Nuclear Power Engineering

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"Development of the MATLAB tool for modeling of the critical flow phenomena"

Main purpose:

Development of the MATLAB tool/package/function for fast and easy prediction of critical-flow parameters in valves or pipe breaks.

Assumptions:

In order to properly obtain the result of this problem, certain assumptions need to be stated. Functions operate in range of temperature from 0 °C to 2000 °C and in pressures from 0 bar to 1000 bar. For the function to work correctly, pressure in the second container should be lower than in the first container. Simple diagram describing the problem and showing assumptions is presented below.

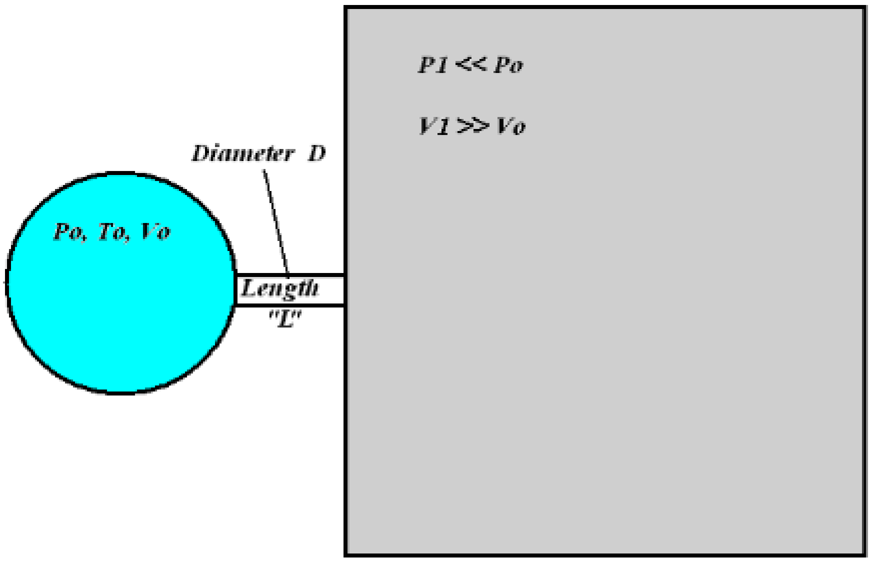

Figure 1 Diagram of the problem with properties assumptions. [3]

The most problematic part of this problem is case of two-phase critical mass flow between two containers. Speed of sound in each phase is different, so certain assumptions need to be modelled to calculate the critical mass flow. For this program, Homogeneous Equilibrium Model (HEM) is used. It is one of the first and simplest models used for this problem. Two main assumptions are employed: velocities of both phases are the same, and both phases are in thermodynamic equilibrium. They allow to treat the mixture as a single fluid, so that the speed of sound is the same in whole mixture. Below is presented methodology of calculation of the mass flux in HEM model. For finding the critical mass flux, iterative solution is implemented, which searches for maximal value of the mass flux for given stagnation pressure. [1]

$$G = \rho_h(p, s_0)\sqrt{2[i_0 - i(p, s_0)]} \tag{1}$$

$$i = i_f(p) + x * i_{fg}(p) \tag{2}$$

$$\rho_h{}^{-1} = \rho_f(p)^{-1} + x[\rho_g(p)^{-1} - \rho_f(p)^{-1}] \tag{3}$$

$$x = \frac{s_0 - s_f(p)}{s_{fg}(p)} \tag{4}$$

For the single-phase flows other assumptions had to be made. The gas is treated as an ideal gas, while the fluid is assumed to be incompressible. [1] In the latter case it means that the critical mass flux cannot be obtained, and the maximal mass flux will be present in the case when the pressure in the second container is equal to 0 bar. Below is presented the formula for the mass flux of incompressible fluid between two containers. [2]

$$G = \rho v_{1-2} \; = \sqrt{2\rho(P_1 - P_2)} \tag{5}$$

Instruction:

Function "critical_flow" can be used for calculation of critical parameters of water, vapour and wet steam flows. Function operates in two modes. In case 1 cross-section of connecting valve, temperature and pressure in both containers are known. Function will calculate critical pressure and critical mass flow.
In case 2 mass flow in the valve, temperature and pressure in both containers are known. Function will calculate critical pressure and critical cross-section area.
In both cases function check the phase of the flow, tells if flow between containers will be critical, and if it isn't, function will calculate values of mass flux and cross-section area for this case.
Here is presented step-by-step instruction of operation of the function:

1. Function asks to choose in which mode it should operate. User can choose between two cases. 1 – for the problem of unknown mass flux in the valve connecting two containers, and 2 – for problems regarding unknown cross-section area of the valve. Type "1" or "2" to choose between cases.
2. After choosing the case, function will ask to input initial parameters of both containers (pressure and temperature) and, depending on the case chosen, either the mass flow or the cross-section area of the valve. In both cases, all values should be positive, temperature should be lower than 2000 °C, and pressure should be lower than 1000 bar. User can also obtain exact value of saturation temperature for previously set pressure by typing "0" when function asks

for temperature input. This allows for implementation of the function in two-phase flow problems.

3. Function checks the phase of the flow.
4. With that information, function chooses adequate method of calculation of the critical pressure and critical mass flux.
5. Function compares obtained critical pressure to pressure in the second container. If the pressure is lower or the same as the critical pressure, than function states that flow is critical. Using critical mass flux, function calculates either the cross-section area or the mass flow.
6. If the pressure in the second container is higher than the critical pressure, than function states that flow is subcritical and chooses correct method of calculation of either the mass flow or the cross-section area for given phase of the flow.

Structure:

Function "critical_flow" is the main function, which utilises the "XSteam" [4] functions for all steam and water calculations. It also uses a number of other functions for other tasks. Below is presented a table, in which names of the functions, input, output parameters and descriptions are listed.

Name	Input	Output	Description
check_if_critical_flow	P2, Pcrit	String "Critical flow" "Subcritical flow"	Checks if pressure in second container is low enough to obtain critical flow
`check_water_flow_state`	P1, T1	String "Liquid" "Superheated Vapour" "Two-Phase"	Checks initial phase of the water in first container. It also checks if all initial parameters in the container were set properly.
`critical_two_phase_flow_mass_flux`	P1	Gcrit, Pcrit	Calculates critical pressure and critical mass flux in the valve. It uses iterative method to find the highest value of mass flux for given initial pressure.
`input_pressure_temperature_cross_section`	-	P1, T1, P2, T2, A	Used for collection of data for Case 1. User can manually write data to the program. User can obtain exact saturation temperature for pressure by typing "0".
`input_pressure_temperature_mass_flow`	-	P1, T1, P2, T2, W	Used for collection of data for Case 2. User can manually write data to the program. User can obtain exact saturation temperature for pressure by typing "0".

`LiquidCrossSection`	P1, T1, P2, W	A	Used for calculation of cross-section area of the valve for single phase liquid flow. Liquid is assumed to be incompressible.
`LiquidMassFlow`	P1, T1, P2, A	W, Wmax	Used for calculation of mass flow and maximal possible mass flow for single phase liquid flow. Liquid is assumed to be incompressible.
`mflux`	P1, s0, h0	G	Used for calculation of the mass flux of two phase flow using HEM formulation.
`singlePhaseCrossSection`	P1, T1, W	Acrit, Pcrit	Used for calculation of critical cross-section area and critical pressure of single phase, ideal gas flow.
`singlePhaseMassFlow`	P1, T1, A	Wcrit, Pcrit	Used for calculation of critical mass flow and critical pressure of single phase, ideal gas flow.
`SubcriticalSinglePhaseCrossSection`	P1, T1, P2, W	A	Used for calculation of cross-section area of subcritical single phase ideal gas flow
`SubcriticalSinglePhaseMassFlow`	P1, T1, P2, A	W	Used for calculation of mass flow of subcritical single phase ideal gas flow
`XSteam [4]`	-	-	Versatile tool for calculation of various water/steam properties.

Table 1 List of functions utilised in function "critical_flow"

Result confirmation:

To check if the solution to the problem for two-phase critical flow is correct, comparison between previously implemented HEM formulation in Python code by H.Anglart, was performed. In figure 2, results from H.Anglart are presented, while in figure 3 results obtained from series of calculations using “mflux” function are shown.

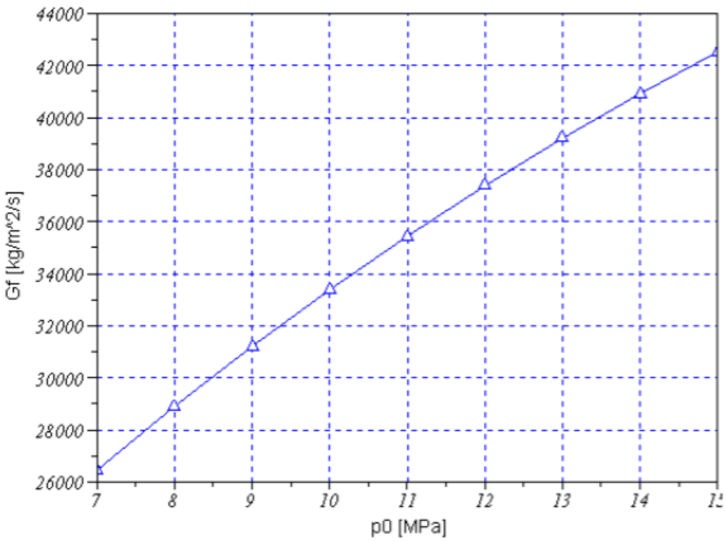

Figure 2 HEM formulation results of critical mass flux compared to stagnation pressure H.Anglart.[1]

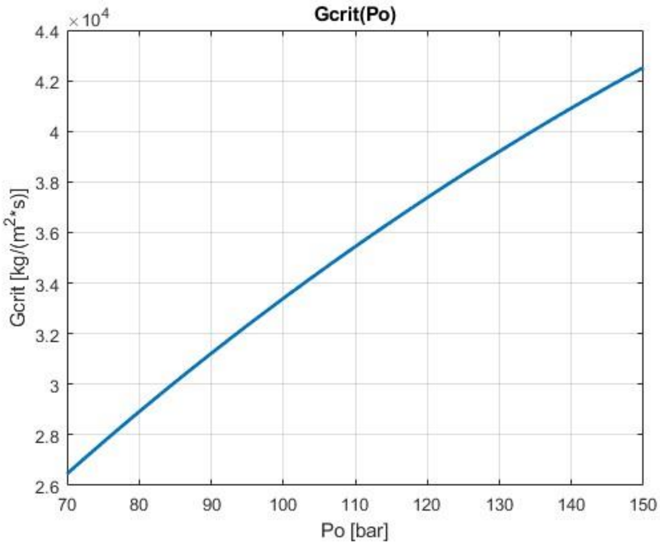

Figure 3 Results of critical mass flux compared to stagnation pressure obtained using “critical_flow” function.

As can be seen, results are almost identical, which means that HEM formulation was implemented correctly in the “critical_flow” function.

References

[1] Anglart, H. (2015). *Thermal-Hydraulics in Nuclear Systems.* Warsaw: Institute of Heat Engineering - Warsaw University of Technology.

[2] Neil E. Todreas, M. S. (2021). *Nuclear Systems, Volume 1, Thermal Hydraulics Fundamentals, Third Edition.* Boca Raton: CRC Press.

[3] Holmgren, M. (2007, siepień 1). *MathWorks.* Retrieved from MathWorks: https://www.mathworks.com/matlabcentral/fileexchange/9817-x-steam-thermodynamic-properties-of-water-and-steam

[4] Joseph S. Miller, P. (n.d.). *Nuclear Regulatory Comission.* Retrieved from Nuclear Regulatory Comission: https://www.nrc.gov/docs/ML1214/ML12142A162.pdf