Models and Algorithms for Determining the Safety Valves Critical Flow at Petrochemical Facilities

A. V. Nikolin and E. R. Moshev

Abstract The chapter deals with the problem of automating the process of determining the critical flow of safety valves. The analysis of normative-technical and scientific-technical literature on the object of research is given. It is shown that in the available literature there are no models and algorithms that allow automating the process of determining the critical flow rate of safety valves. With the help of a systematic approach, the analysis of the process of determining the emergency flow rate of safety valves as an object of computerization is carried out. As a result of the analysis, it was found that this process contains heuristic knowledge and can be formalized using the methods of the theory of artificial intelligence. A functional model for determining the critical flow rate of safety valves as an organizational and technological process is presented, and the necessary heuristic and computational algorithms are provided. The developed models and algorithms make it possible to create a cyber-physical system that will ensure the determination of the critical flow of safety valves in an automated mode.

Keywords Safety valve · Relief pressure · Critical flow · Overpressure · Functional model · Heuristic-computational algorithm · Cyber-physical system

1 Introduction

To prevent emergencies, special technical devices called safety valves (SV) are installed on the equipment and pipelines of petrochemical plants. They are designed to relieve the pressure that exceeds the value allowed by industrial safety rules. The most important parameter that ensures the correct choice of the brand and size of the valve is the value of the critical flow rate of the substance in the device. The critical

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flow rate here means the minimum throughput of the SV, which guarantees that the pressure in the vessel or pipeline does not rise more than the value allowed by the normative and technical documentation.

The critical flow rate of safety valves must be determined in strict accordance with the requirements of industrial safety rules and it is a complex engineering and technical problem [1], the solution of which depends on many factors, e.g. chemical composition, pressure, temperature, and volume of the substance in the apparatus; the parameters and type of the technological process taking place in specific equipment for which it is necessary to select an SV. At the same time, the process of determining the critical SV consumption takes a long time, which is due to the presence of a large number of various routine operations related to the search for reference data, their processing, as well as the procedures for making intelligent decisions [2, 3]. It is possible to simplify and accelerate the determination of critical SV consumption if you create and apply special software - a cyber-physical system (CPS) [4–7]. Analysis of scientific and technical literature did not reveal models [8–13] and algorithms [14–16] that can be used without correction for the development indicated by the CPS. Based on the foregoing, the purpose of this study was to create models and algorithms that automate the determination of critical SV consumption.

To achieve this goal, the following tasks were formulated:

- to analyze the process of determining the critical consumption of an SV as an object of computerization;
- to develop a functional model (FM) for determining critical SV consumption as an organizational and technological process;
- to develop algorithms that formalize the procedures for determining critical SV consumption.

2 The Process of Determining the Critical Flow of Safety Valves as an Object of Computerization

The analysis of the normative and technical documentation and scientific and technical literature established that the process of determining critical SV consumption consists of three main stages: determining the characteristics for calculating critical SV consumption; calculating critical SV consumption; checking the critical SV consumption for a fire condition. In this case, the most difficult stage in terms of computerization is the second stage—the calculation of the critical flow rate. This is because the critical flow has complex relationships with the parameters of a specific technological process and its hardware design, and engineering and technical calculations require good knowledge of chemical technology. At the same time, there are dependencies between the SV characteristics and the working environment, which are discrete in most cases. The analysis of the procedures for determining critical SV consumption showed that they can be formalized using the methods of the theory of artificial intelligence [2, 3], which allows them to be automated.

3 Development of a Functional Model for Determining the Critical Flow of Safety Valves

As a result of the analysis of knowledge about the subject of research, carried out using a systematic approach [17, 18], a logical-informational model was developed that formalizes the definition of critical SV consumption as an organizational and technological process. The model is described following the methodology of structural analysis and design SADT (Structured Analysis & Design Technique) (Fig. 1). The SADT methodology [19, 20] was chosen since it is often used in the development of complex systems and many cases are considered an integral part of CALS technologies [21, 22]. In the Russian Federation, it is also widely known as a functional modelling methodology.

The developed functional model (FM) is distinguished by the use of a systematic approach and account of the complex relationships between the various stages of determining the critical consumption of an SV, as well as the connection with data- and knowledgebases, which allows automating the execution of the steps indicated above, and, at the same time, ensure a high information exchange rate. As an example of FM detailing, the decomposition of block A12 (Fig. 2) of diagram A1 is presented, which shows the relationship between various functions of the procedure for calculating the critical consumption of SVs installed on technological equipment. In Fig. 2 P1 is the full opening pressure of the valve; $G^{CR}{}_{SUP}$ is power flow of the column in the emergency mode during P_1; e is a mass fraction of steam in the feed (fraction of distillate); $i^{L.N}{}_{SUP}$ is heat content of liquid feed in the normal mode at P_P; P_P is

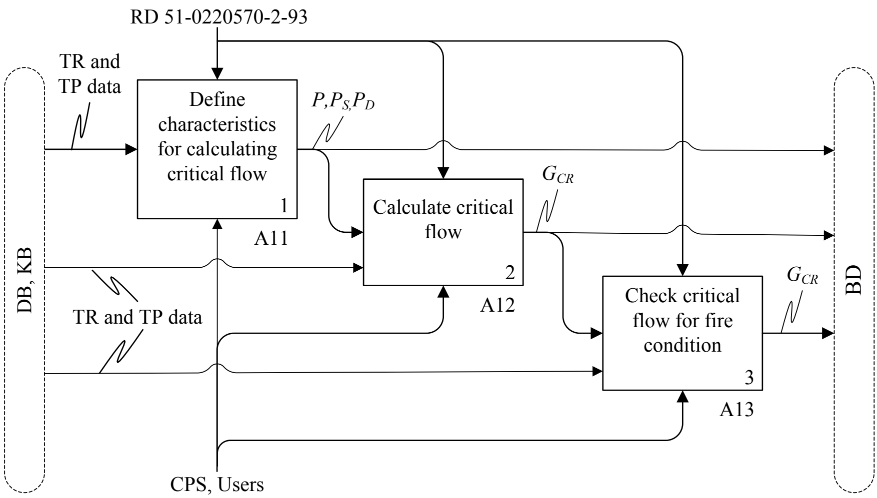

Fig. 1 Diagram A1 of the functional model for determining the critical flow of safety valves: TR is technological regulations; TP is a technical passport of the vessel; G_{CR} is the critical flow of the working medium; P is the SV working pressure; P_D is the SV design pressure; P_S is the SV setting pressure; DB is database; KB is knowledge base

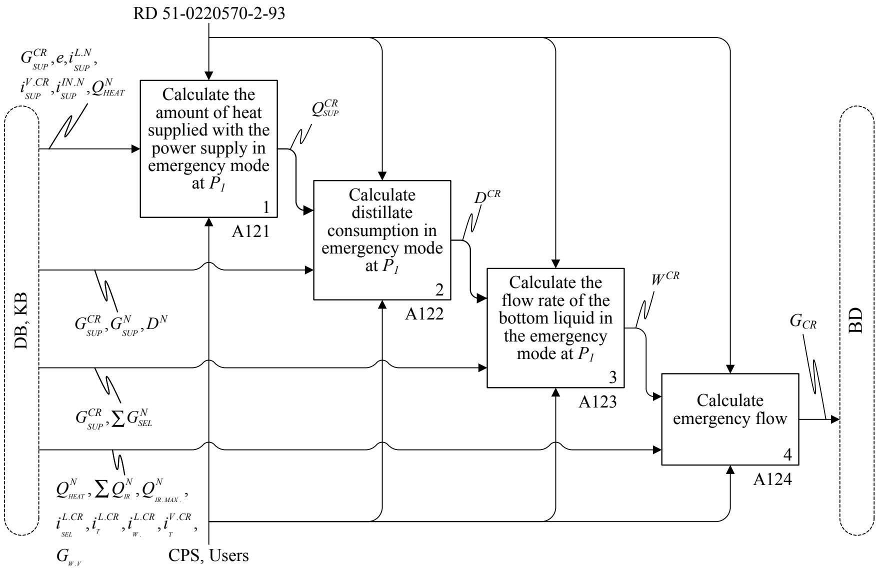

Fig. 2 Decomposition of block A12 of diagram A1

process pressure; $i^{V.CR}{}_{SUP}$ is heat content of supply vapour in the emergency mode during P_1; $i^{IN.N}{}_{SUP}$ is heat content of the feed at the input to the feed heater in the normal mode at P_P (adopted according to the project); $Q^N{}_{HEAT}$ is thermal load of the power heater in the normal mode at P_P; $Q^{CR}{}_{SUP}$ is the amount of heat supplied with feed in the emergency mode during P_1; $G^N{}_{SUP}$ is power consumption of the column in the normal mode at P_P (adopted according to the project); D^N is distillate consumption in the normal mode at P_P (adopted according to the project); D^{CR} is distillate consumption in the emergency mode during P_1; $\Sigma G^N{}_{SEL}$ is the sum of the intermediate selection flow rates in the normal mode at P_P (adopted according to the project); W^{CR} is consumption of bottom liquid in the emergency mode during P_1; $\Sigma Q^N{}_{IR}$ is the total heat load of intermediate circulating irrigation in normal mode; $Q^N{}_{IR.MAX}$ is the heat load of one of the intermediate circulating irrigations, which has the highest value, in normal mode at P_P (adopted according to the project); $i^{L.CR}{}_{SEL}$ is the heat content of the intermediate withdrawal fluid in emergency mode at P_1; $i^{L.CR}{}_T$ is the heat content of the liquid product at the top of the column in emergency mode P_1; $i^{L.CR}{}_W$ is the heat content of the liquid vat residue in emergency mode atP_1; $i^{V.CR}{}_T$ is the heat content of steam at the top of the column in emergency mode atP_1; G_{WV} is the flow of water vapour (inert gas) supplied to the column for stripping (taken into account only if the pressure of water vapour is higher than P_1).

4 Algorithms to Automate the Determination of Critical Flow of Safety Valves

As a mechanism for the implementation of the functions specified in the FM blocks, the corresponding algorithms have been developed. Examples of algorithms that make it possible to automate the execution of block A12 for different types of equipment are shown in Figs. 3 and 4. Figure 3 shows an algorithm for determining the critical flow rate of SVs installed on distillation columns.

This algorithm formalizes the process of determining the critical flow rate of the SV installed on the rectification columns, as well as the following characteristics: the amount of heat supplied with the power supply in the emergency mode (at P_1) $Q^{CR}{}_{SUP}$; distillate consumption in the emergency mode (during P_1) D^{CR}; the flow rate of bottom liquid in the emergency mode (at P_1) W^{CR}. The algorithm differs in that with the help of the given initial data (a heater at the power supply H, the type of heater at the power supply TH, regulation of the supply temperature at the outlet), it allows us to automate computational and intelligent decision-making procedures when determining the critical consumption of SVs installed on the distillation columns, following the requirements of the normative and technical documentation.

Figure 4 shows an algorithm for determining the critical flow rate of the SVs installed on other (not rectification columns) process vessels and pipelines, in particular, tanks; separators; degassers; absorbers; adsorbers; phase separators; liquid pipelines, and vessels filled with liquid and designed for the pressure of the supply source; pipelines on the lower pressure side downstream of the pressure regulators; discharge lines after a pump or compressor.

The following designations are used in the algorithm (Fig. 4): Lis SV location (for example, LPis liquid pipeline; IP is injection pipeline); TE is the type of equipment (for example, PT is process tank; SPR is separator; DGS is degasser; ABR is absorber; ABR is adsorber; ADR is adsorber; VCFLis vessel filled with liquid); T_1 is the working temperature of the liquid in the neighbour (pipeline); T_2 is the maximum temperature of the liquid in the vessel (pipeline) (taken equal to 50 °C); V_V is the initial volume of liquid in the vessel (pipeline) at temperature T_1; ρ_L is the density of the liquid at temperature T_1; $\beta_L$is the coefficient of volumetric expansion of the liquid.

An example of a heuristic-computational algorithm that automates the execution of block A13 is shown in Fig. 5.

In the algorithm (Fig. 5), the following designations are used: SAM is the medium aggregation state (where L is liquid, G is gas, G/L is gas/liquid); TC is the type of medium (where FL is flammable liquids, LG is liquefied gas, CG is combustible gas, etc.); L is the SV location (for example, BSV is between the shut-off valves); TE is the type of equipment; RE is refrigeration equipment; PH is pipeline heating; TI is thermal insulation; r is the latent heat of vaporization of a liquid at discharge pressure P_D (for safety valves installed on a heated pipeline with flammable liquids or liquefied gases between shut-off valves), or the latent heat of vaporization of a liquid at temperature t_L (for vessels completely filled with a liquid phase or containing a

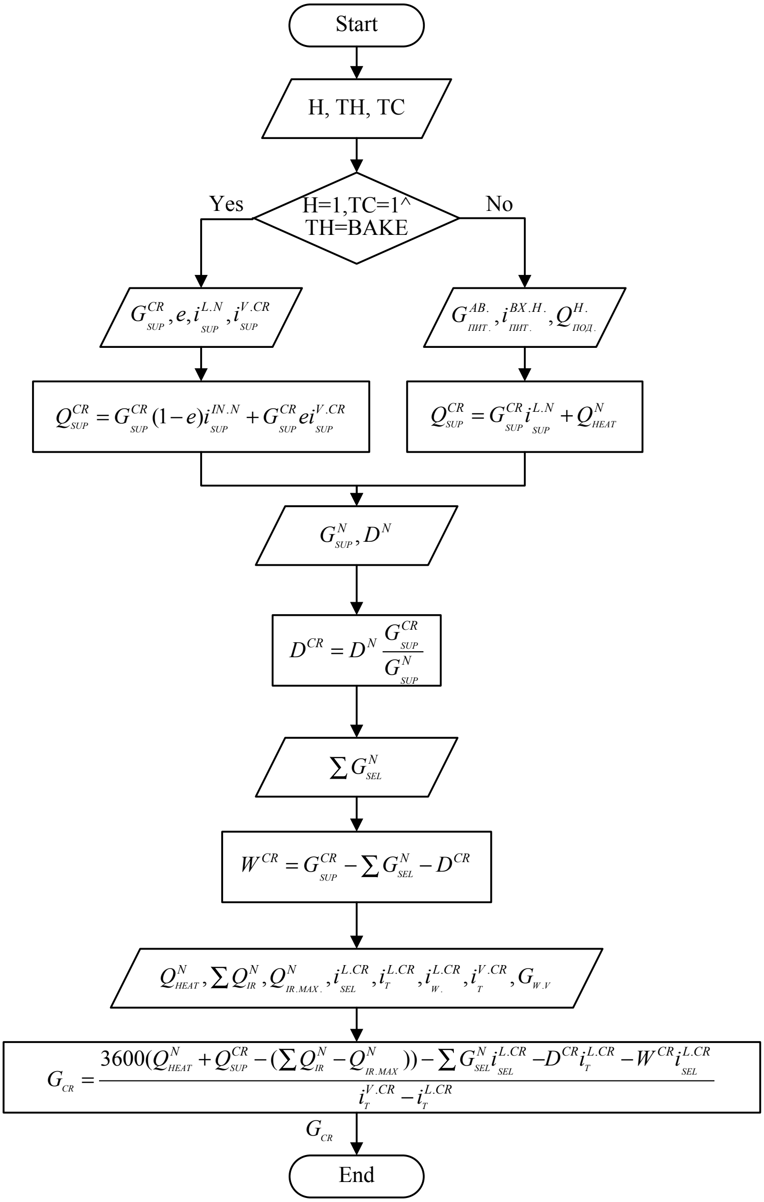

Fig. 3 Block diagram of a heuristic-computational algorithm for determining the critical consumption of SVs installed on rectification columns

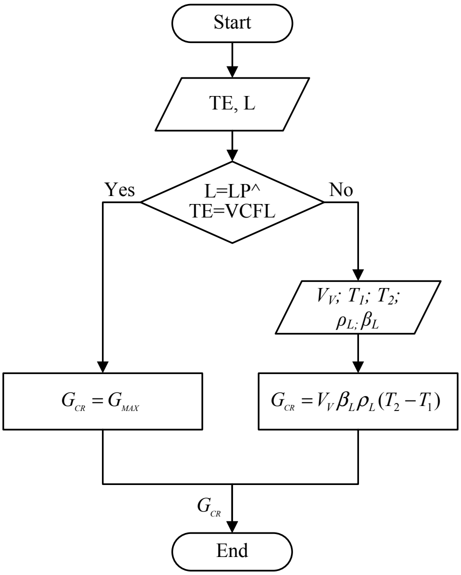

Fig. 4 Block diagram of a heuristic-computational algorithm for determining the critical consumption of SVs installed on process vessels and pipelines

liquid and vapor phase); t_S is satellite temperature; t_{BPL} is the boiling point of the liquid at discharge pressure P_D; K is heat transfer coefficient when heating with a steam or water satellite; F_H is the surface of the heated pipeline section between the shut-off valves; F_{WS} is wetted surface of the apparatus; t_G is the temperature of the gas-air mixture that washes the outer surface of the apparatus in case of fire; t_{BL} is the boiling point of the liquid at the full opening pressure of the safety valve; K_L is the overall coefficient of heat transfer from the ambient air through the apparatus wall to the liquid; F_O is total outer surface of the apparatus; t_V is the temperature of gases (vapors) in the apparatus during normal operation; C_V is the heat capacity of gas (vapor) at the discharge pressure P_D; K_V is the overall coefficient of heat transfer from the ambient air through the apparatus wall to the gas (vapor).

The developed algorithm formalizes the verification process of the calculated critical flow rate of a spring-loaded safety valve for a fire condition. The algorithm differs in that with the help of the given initial characteristics, it allows automating computational and intelligent decision-making procedures when checking the calculated critical SV consumption for a fire condition following the requirements of regulatory and technical documentation.

5 Conclusion

Thus, as a result of this study, by analyzing the regulatory and technical documentation and scientific and technical literature, as well as using a systematic approach to the process of determining critical SV consumption, the following were developed:

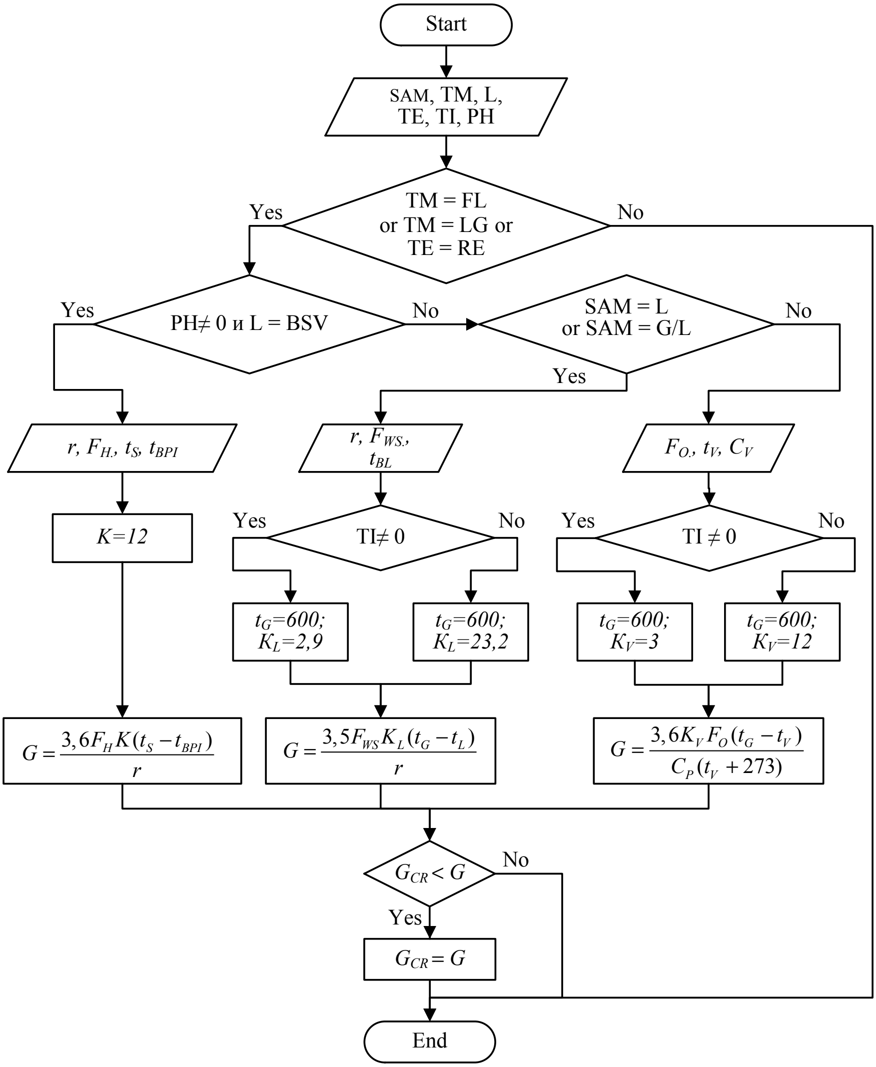

Fig. 5 Block diagram of a heuristic-computational algorithm for checking critical SV consumption for a fire condition

- A functional model for determining the critical flow rate of safety valves as an organizational and technological process, which is distinguished by the systematic approach and account of complex relationships between various stages of characterization for calculating the SV critical flow rate, as well as by connection with data- and knowledge bases, which allows automating the procedure for determining the critical flow of an SV while providing a high speed of data exchange.

- Heuristic-computational algorithms allow automating computational and intelligent decision-making procedures when performing the functions specified in the functional model block and when determining critical SV consumption, following the requirements of the normative and technical documentation.

The developed models and algorithms make it possible to create a CPS, the use of which will accelerate the search and data processing procedures, as well as reduce the number of subjective errors in determining critical SV consumption, which will increase the quality of SV selection, and, consequently, the industrial safety and economic efficiency of petrochemical facilities in general.

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