Models and Algorithms for Selecting Safety Valves for Petroleum Industries

A. V. Nikolin and E. R. Moshev

Abstract The chapter deals with the problem of automatic determination of the design and technological characteristics of safety valves. The normative-technical and scientific-technical literature devoted to the object of research was analyzed. It is shown that in the literature, there are no models and algorithms that allow automating the process of defining the above-mentioned characteristics. The functional model of determining safety valve characteristics as an organizational and technological process is presented. Production models of knowledge representation and also heuristic-computing algorithms for choosing the required characteristics are developed. The models and algorithms enable creating the problem-oriented cyber-physical system which will define the design and technological characteristics of safety valves in an automated mode.

Keywords Safety valve · Effective seat area · Critical flow · Overpressure · Functional model · Production model · Heuristic-computing algorithm · Cyber-physical system

1 Introduction

To prevent accidents in petrochemical industries, safety valves (SV) are installed on process equipment, including pipelines. These are fittings designed for emergency relief of operating pressure if it exceeds the amount allowed by the technological regulations. The process of determining the SV characteristics that meet the requirements of industrial safety rules is a complex engineering task [1], the results of which depend on the chemical composition, pressure, temperature, and volume of the working medium, as well as the parameters and type of the technological process

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that occurs in a particular unit of equipment. According to the above, the implementation of this process can be lengthy and require not only routine operations of retrieval and processing of technological and regulatory data but also procedures for making intelligent decisions [2, 3]. It is possible to simplify and speed up the determination of SV characteristics if you create and apply special software - a problem-oriented cyber-physical system (CPS) [4–7]. However, the analysis of scientific and technical literature did not reveal models [8–13] and algorithms [14, 15] that could be used for the specified CPS development. Based on the above, the purpose of this study was to create models and algorithms that allow you to automate the process of determining the SV characteristics.

To achieve this goal, the following tasks were formulated:

- analyze the process of determining the SV characteristics as an object of computerization;
- develop a functional model (FM) for determining the SV characteristics as an organizational and technological process;
- develop algorithms to automate SV selection; and
- develop models for the representation of knowledge and data about SVs that will automate the process of determining their characteristics.

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

The analysis of normative and technical documentation and scientific and technical literature established that the process of determining the SV characteristics consists of four main stages: calculation of the critical flow rate of the working medium, calculation of the SV effective seat area, SV brand selection, and SV quantity calculation. Moreover, the first and second stages are the most difficult in terms of computerization. This is due to the fact that the critical flow rate of the working medium has complex relationships with the parameters of a particular technological process and its hardware design, and it involves engineering calculations requiring good knowledge of chemical technology. The procedure for determining the SV effective seat area contains not only the data retrieval and processing operations, but also the procedures for making intelligent decisions, as was mentioned above. At the same time, there are dependencies between the SV and the working medium characteristics, which in most cases are discrete. Analysis of the procedures for determining the SV characteristics showed that a significant part of them can be formalized using the theory of artificial intelligence [2, 3], which allows their automation.

3 Development of a Functional Model for Determining the Safety Valves Characteristics

As a result of the analysis of knowledge about the subject of research performed using the system approach [16, 17], a logical-information model was developed that formalizes the solution to the problem of choosing the SV as an organizational and technological process. The model is described following the methodology of structural analysis and design SADT (Structured Analysis and Design Technique) (Fig. 1). The SADT methodology [18, 19] was chosen because it is often used in the development of complex systems and in many cases it is considered an integral component of CALS technologies [20, 21]. In the Russian Federation, it is also widely known as the functional modeling methodology.

The developed FM differs in applying a system approach and taking into account the complex relationships between the various stages of determining the SV characteristics, as well as in connection with data- and knowledge bases, which allows automating the implementation of the above steps while ensuring high-speed information exchange. As an example of FM detailing, the decomposition of block A2 (Fig. 2) of diagram A0 is presented, which shows the relationships between various functions of the procedure for calculating the SV effective seat area, as well as data- and knowledge bases.

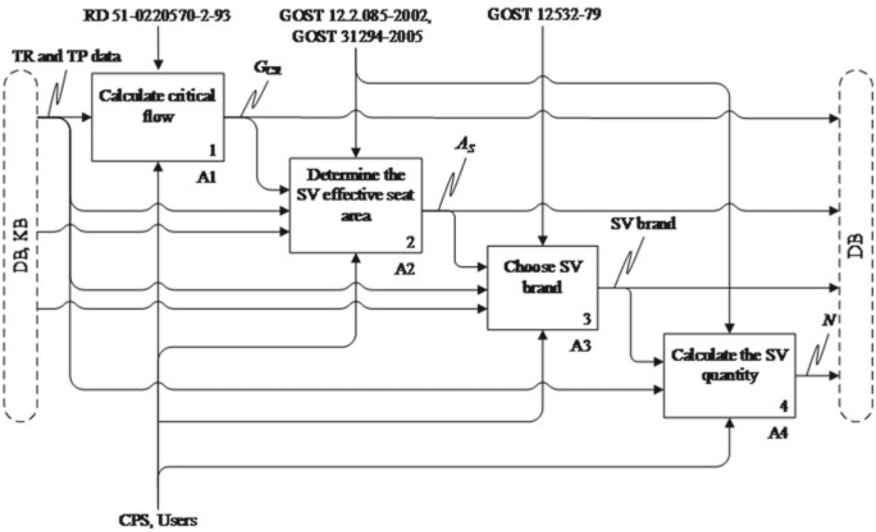


Fig. 1 Diagram A0 of the functional model for determining the safety valves characteristics: TR—technological regulations; TP—technical passport of the vessel; G_{CR}—critical flow rate of the working medium; A_S—the SV effective seat area; N—SV quantity; DB—database; KB—knowledge base

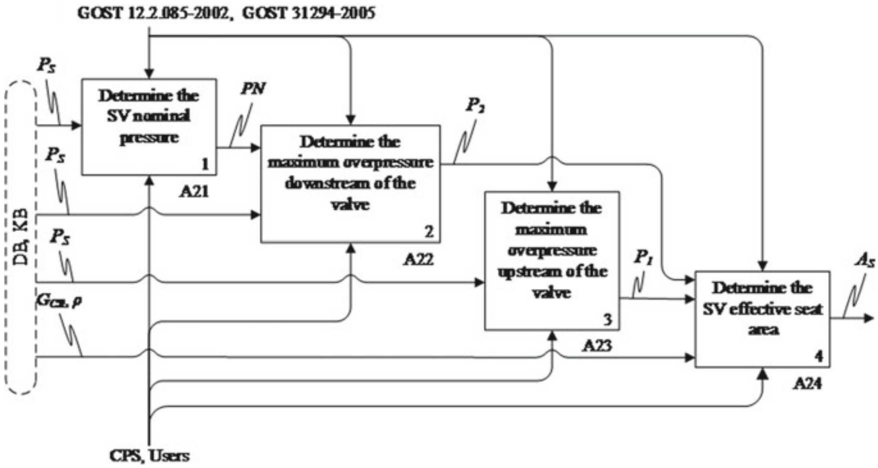


Fig. 2 Decomposition of block A2 of diagram A0: P_S is valve setting pressure; *PN* is the SV nominal pressure; P_2 is the highest overpressure downstream of the valve (overpressure downstream of the valve in the position of its full opening); P_1 is the highest overpressure upstream of the valve (overpressure upstream of the valve equal to the pressure of full opening); ρ is the density of steam, gas or liquid upstream of the valve

4 Development of Algorithms to Automate the Safety Valves Characterization

As a mechanism for implementing the functions indicated in the FM blocks, the corresponding heuristic-computational algorithms were developed. An example of an algorithm that automates the execution of blocks A21 and A22 is shown in Fig. 3. This algorithm formalizes the process of determining the following SV characteristics: nominal pressure PN; the highest overpressure downstream of the valve P2 and the possible nominal diameter values of the outlet pipe DNOUT. Using a given initial characteristic of the setting pressure PS and production models of knowledge representation (Table 1), the algorithm automates computational and intelligent decision-making procedures for determining SV characteristics as required by normative and technical documentation.

An example of the heuristic-computational algorithm that automates the execution of block A24 is shown in Fig. 4.

The following designations are used in the algorithm (Fig. 4): β is pressure ratio; β_{CR} is a critical pressure ratio; B_1, B_2, B_3 are coefficients for determining the effective seat area for gases and water vapor; k is the adiabatic index; R_{SP} is gas constant.

The developed algorithm formalizes the process of determining the effective seat area of a spring safety valve. Using the specified initial characteristics of the working medium (P2, GCR, ρ) and production models for the knowledge representation, the algorithm automates computational and intelligent decision-making procedures

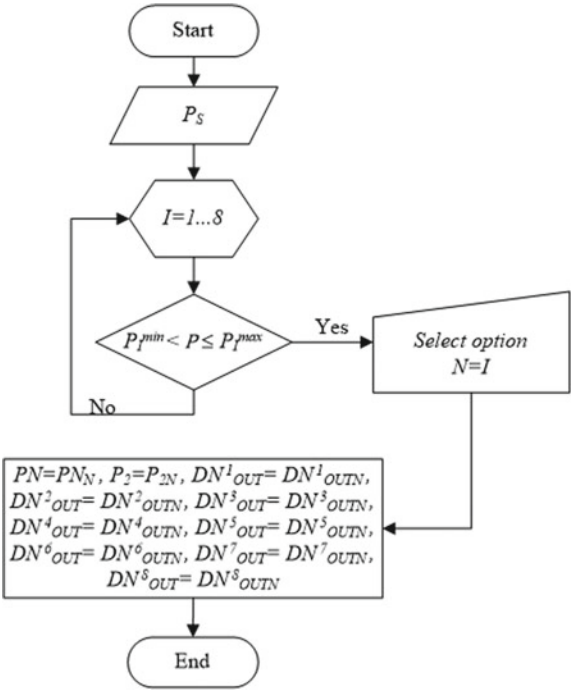


Fig. 3 Block diagram of a heuristic-computational algorithm for determining the SV characteristics: nominal pressure *PN*; the highest overpressure downstream of the valve P_2; possible nominal pressure values of the outlet pipe DN_{OUT}

Table 1 Production model for representing valve performance knowledge

Setting pressure P_S kgf/cm^2		Valve nominal pressure PN, kgf/cm^2	P_2, kgf/cm^2	Nominal diameter of the outlet pipe DN_{OUT}, mm							
min	max										
0.5	6	6	2.5	80	100	150	200	300	350	400	–
>6	16	16	6	25	40	65	80	100	150	200	300
>16	40	40	16	25	40	65	80	100	150	200	300
>40	63	63	25	25	40	65	80	100	150	–	–
>63	100	100	40	25	40	65	80	100	150	–	–
>100	160	160	40	15	25	40	65	80	100	–	–
>160	250	250	40	15	25	40	65	80	–	–	–
>250	320	320	40	15	25	32	40	–	–	–	–
>320	400	400	40	15	25	40	65	–	–	–	–
Applicability conditions		Required specifications									

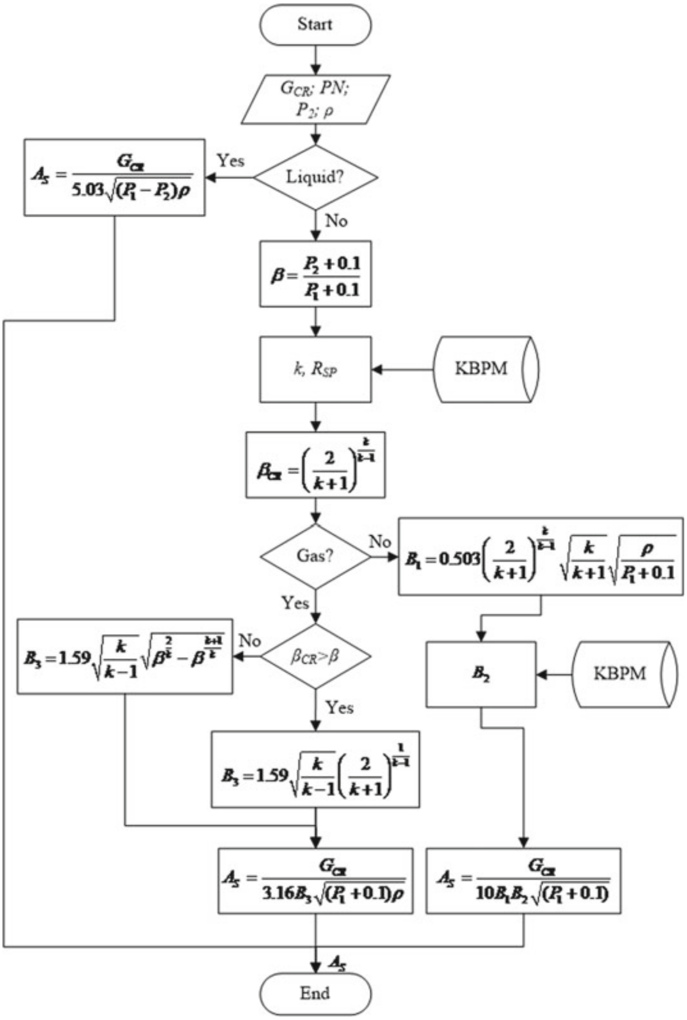


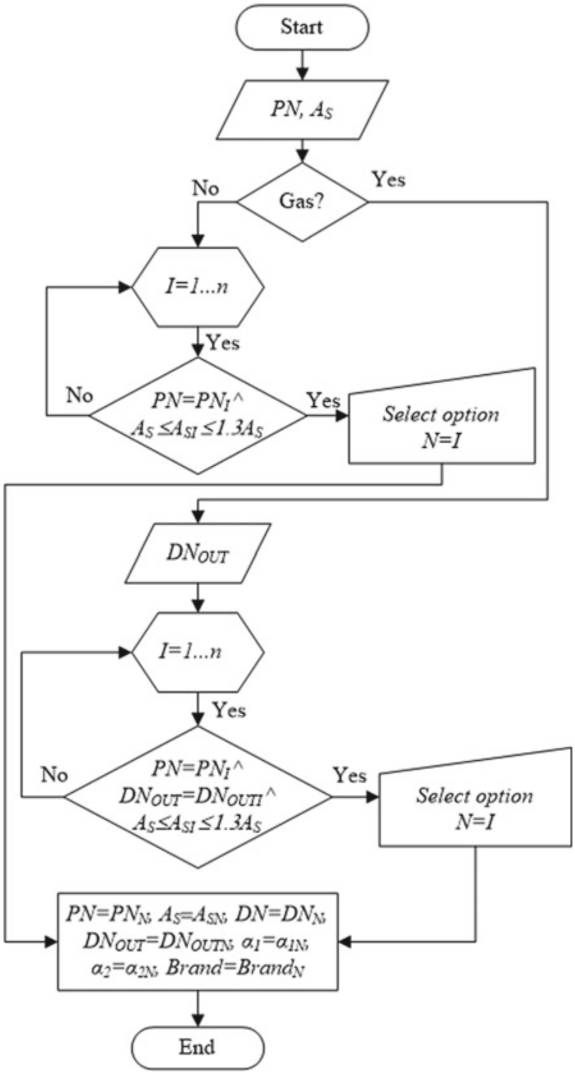
Fig. 4 Block diagram of a heuristic-computational algorithm for determining the effective seat area of a safety valve

for determining the SV effective seat area as required by regulatory and technical documentation.

An example of the algorithm that automates the execution of block A3 is shown in Fig. 5.

With the help of the specified initial parameters (PN, DNOUT, AS) and the database, the algorithm (Fig. 5) allows you to automate computational and intelligent decision-making procedures for selecting SVs as required by regulatory and technical documentation.

Fig. 5 The block diagram of the SV brand selection algorithm



5 Development of Models for the Representation of Knowledge and Data on the Rules for Determining SV

To ensure the automated operation of the algorithm for determining the effective seat area, production models for representing knowledge used in the methods of the theory of artificial intelligence were created [5, 7]: of valve characteristics, of B2 coefficient, and gas characteristics.

Table 2 Production model for B_2 coefficient knowledge representation

β	k	B_2	β	k	B_2	β	k	B_2
0.5	1.1	1	0.577	1.1	1	0.7	1.1	0.965
0.5	1.135	1	0.577	1.135	1	0.7	1.135	0.955
0.5	1.310	1	0.577	1.310	0.99	0.7	1.310	0.945
0.5	1.4	1	0.577	1.4	0.99	0.7	1.4	0.93
0.528	1.1	1	0.586	1.1	1	0.8	1.1	0.855
0.528	1.135	1	0.586	1.135	0.98	0.8	1.135	0.85
0.528	1.310	1	0.586	1.310	0.99	0.8	1.310	0.83
0.528	1.4	1	0.586	1.4	0.99	0.8	1.4	0.82
0.545	1.1	1	0.6	1.1	0.99	0.9	1.1	0.655
0.545	1.135	1	0.6	1.135	0.957	0.9	1.135	0.65
0.545	1.310	1	0.6	1.310	0.975	0.9	1.310	0.628
0.545	1.4	0.99	0.6	1.4	0.99	0.9	1.4	0.62
Applicability conditions			Applicability conditions			Applicability conditions		

An example of a production model for the valve's characteristics is given in Table 1. This model formalizes the regulatory relationship between the setting pressure (of the safety valve) PS on the one hand and the SV characteristics (PN, P2, DNOUT—the SV outlet pipe nominal diameter) on the other hand.

An example of a production model for the coefficient B_2 is shown in Table 2. This model takes into account the correlation between the B_2 coefficient on the one hand and the adiabatic index k as well as the pressure ratio β (the ratio of the highest overpressure downstream of the valve to the highest overpressure upstream of the valve) on the other.

An example of a production model for the characteristics of gases is presented in Table 3. The model establishes a mutual relationship between the type of gas on the one hand and its gas constant R_{SP}, as well as the adiabatic exponent k on the other. The adiabatic index k is necessary for calculating the critical ratio of pressures (β_{CR}), coefficients B_1 and B_3 as well as for determining the B_2 coefficient.

6 Conclusion

Thus, as a result of this study, using the analysis of regulatory and technical documentation and scientific and technical literature, as well as a system approach to the process of determining the SVs characteristics, the following were developed:

- A functional model for the selection of safety valves as an organizational and technological process, characterized by applying a system approach and taking into account the complex relationships between the various stages of determining

Table 3 Production model for gas characteristics knowledge representation

Gas	Adiabatic index k	Gas constant R_{SP}, kgf·m/(kg·°C)
Nitrogen	1.4	30.25
Butane	1.10	14.60
Hydrogen	1.41	420.00
Methane	1.30	52.6
Carbon oxide	1.40	30.25
Propane	1.14	19.25
Hydrogen sulfide	1.30	24.90
Ethane	1.22	28.2
Ethylene	1.24	30.23
Applicability conditions	Required specifications	

the SV characteristics, as well as by connecting to databases and knowledge, which allows automating the procedure for selecting the SV and providing high speed of information exchange.

- Heuristic-computational algorithms, which, with the help of predetermined initial process characteristics and production models of knowledge representation, enable automated computational and intelligent decision-making procedures for determining SV characteristics as required by regulatory and technical documentation.
- Production models for representing knowledge of the valves and gases characteristics, ensuring the operation of algorithms for calculating and selecting SV characteristics, which formalize regulatory relationships between process parameters on the one hand and SV characteristics on the other.

The developed models and algorithms will make it possible to create a CPS, the use of which will reduce the duration of the data retrieval and processing procedures, as well as the number of subjective errors, which will increase the quality of determining the structural and technological characteristics of SVs, and, consequently, the industrial safety and economic efficiency of petrochemical plants in general.

References

1. Horlacher, H.-B., Helbig, U. (Hrsg.): Rohrleitungsplanung–Grundsätze, Vorschriften, Regelwerke. Rohrleitungen 1, pp. 35–43. Springer Reference Technik.C. (2016)
2. Wu, D., Olson, D.L., Dolgui, A.: Artificial intelligence in engineering risk analytics. Eng. Appl. Artif. Intell. **65**, 433–435 (2017)
3. Russell, S.J., Norvig, P.: Artificial Intelligence: A Modern Approach, 3rd edn. Prentice Hall, New Jersey (2010)

4. Buldakova, T.I., Suyatinov, S.I.: Assessment of the state of production system components for digital twins technology. In: Kravets, A., Bolshakov, A., Shcherbakov, M. (eds.) Cyber-Physical Systems: Advances in Design and Modelling. Studies in Systems, Decision and Control, vol. 259. Springer, Cham (2020)
5. Stepanov, M., Musatov, V., Egorov, I., Pchelintzeva, S., Stepanov, A.: Cyber-physical control system of hardware-software complex of anthropomorphous robot: architecture and models. In: Kravets, A., Bolshakov, A., Shcherbakov, M. (eds.) Cyber-Physical Systems: Advances in Design and Modelling. Studies in Systems, Decision and Control, vol. 259. Springer, Cham (2020)
6. Alekseev, A.P.: Conceptual approach to designing efficient cyber-physical systems in the presence of uncertainty. In: Kravets, A., Bolshakov, A., Shcherbakov, M. (eds.) Cyber-Physical Systems: Advances in Design and Modelling. Studies in Systems, Decision and Control, vol 259. Springer, Cham (2020)
7. Moshev, E., Meshalkin, V., Romashkin, M.: Development of models and algorithms for intellectual support of life cycle of chemical production equipment. In: Kravets, A., Bolshakov, A., Shcherbakov, M. (eds.) Cyber-Physical Systems: Advances in Design and Modelling. Studies in Systems, Decision and Control, vol. 259. Springer, Cham (2020)
8. Guo, F., Zou, F., Liu, J., Wang Z.: Working mode in aircraft manufacturing based on digital coordination model. Int. J. Adv. Manuf. Technol. **98**, 1547-1571. Springer, Cham (2018). http://dx.doi.org/10.1007/s00170-018-2048-0
9. Kim, H., Han, S.: Interactive 3D building modeling method using panoramic image sequences and digital map. Multimedia Tools Appl. **77**(20), 27387-27404. Springer, Cham (2018). http://dx.doi.org/10.1007/s11042-018-5926-4
10. Cheng, J., Liu, Z., Yu, X., Feng, Q., Zeng, X.: Research on dynamic modeling and electromagnetic force centering of piston/piston rod system for labyrinth piston compressor. Proc. Inst. Mech. Eng. Part I: J. Syst. Control Eng. **230**(8), 786–798 (2016)
11. Comelli, M., Gourgand, M., Lemoine, D.: A review of tactical planning models. J. Syst. Sci. Syst. Eng. **17**(2), 204–229 (2008)
12. Moshev, E.R., Romashkin, M.A.: Development of a conceptual model of a piston compressor for automating the information support of dynamic equipment. Chemical and Petroleum Engineering. vol. 49(9–10), pp. 679-685. Springer, Cham (2014). http://dx.doi.org/10.1007/s10556-014-9818-9
13. Elena, Nenni M.: A Cost model for integrated logistic support activities. Adv. Oper. Res. **2013**, 1–6 (2013)
14. Menshikov, V., Meshalkin, V., Obraztsov, A.: Heuristic algorithms for 3D optimal chemical plant layout design. In: Proceedings of 19th International Congress of Chemical and Process Engineering (CHISA-2010), vol. 4, pp. 1425. Prague (2010)
15. Lu, J., Zhu, Q., Wu, Q.: A novel data clustering algorithm using heuristic rules based on k-nearest neighbors' chain. Eng. Appl. Artif. Intell. **72**, 213–227 (2018)
16. Bertoni, M., Bertoni, A., Isaksson, O.: A value-driven concept selection method for early system design. J. Syst. Sci. Syst. Eng. **27**(1), 46–77 (2018)
17. Martin, P., Kolesár, J.: Logistic support and computer aided acquisition. J. Logistics Manage. **1**, 1–5 (2012)
18. Bogomolov, B.B., Bykov, E.D., Men'shikov, V.V. et al.: Organizational and technological modeling of chemical process systems. Theor Found Chem Eng **51**, 238–246 (2017). https://doi.org/10.1134/S0040579517010043

19. Marca, D.A.: SADT/IDEF0 for Augmenting UML, Agile and Usability Engineering Methods. In: Escalona, M.J., Cordeiro, J., Shishkov, B. (eds.) Software and Data Technologies. ICSOFT 2011. Communications in Computer and Information Science, vol. 303. Springer, Berlin, Heidelberg (2013)
20. Meshalkin, V.P., Moshev, E.R.: Modes of functioning of the automated system "Pipeline" with integrated logistical support of pipelines and vessels of industrial enterprises. J. Mach. Manuf. Reliab. **44**(7), 580–592 (2015)
21. Moshev, E.R., Meshalkin, V.P.: Computer-based logistics support system for the maintenance of chemical plant equipment. Theor. Found. Chem. Eng. **48**(6), 855–863 (2014)