**ISSN 1453 – 7303 “HIDRAULICA” (No. 4/2019)**
**Magazine *of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics***

# Modelling and Sensitivity Study of a Firefighting System

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***Abstract:*** *For safe operation of firefighting systems it is essential to study the operation conditions, especially in case of mobile fire pumps, which are sometimes used by firefighters under extreme conditions. Changes in operation parameters can have a serious impact on the amount of water that can be extracted from the system, and thus on the effectiveness of firefighting itself. Therefore, the study of the topic is an important current issue. During this research a simulation model of a firefighting system was created. In this paper the developed model is presented first, which is followed by numerical simulations and a Fuzzy-set based sensitivity study using the model. The aim of the research is to facilitate the optimal operation of firefighting systems and the work of firefighters and to increase the efficiency of firefighting.*

***Keywords****: Firefighting system, operation parameters, numerical simulation, sensitivity study*

## 1. Introduction

Various pumps allow the transport of liquids in piping systems. Within pumps there is a separate group of fire pumps. The continuous examination of their operating conditions is essential for effective firefighting and continuous water supply. Their operation sometimes takes place under extreme conditions, which greatly affects the pump performance and thus the amount of water that can be extracted from the system. In order to facilitate accurate investigations and practical applications a simulation model of a mobile pump-operated firefighting system based on [1] was created as first step. The paper is organized as follows: first the technical parameters of the firefighting system are described, which is followed by the development of the simulation model and a parameter sensitivity study. The paper concludes with the summary of the results and further research tasks.

## 2. Examined firefighting system

In most cases the performance parameters of fire pumps are measured at a suction depth of 1.5 to 3 meters by means of a measuring device placed directly on the discharge port of the pump at various speed limits .During firefighting tasks suction depth of 3 m or less is required in case of built-up basins, therefore this is the starting point for developing our system. During operation of firefighting systems, the change in head may result in a significant performance difference in the amount of water that can be extracted from the system. It can even be decreased to a quarter of the expected amount within a given time interval. Creating optimal operation conditions for firefighting tasks is important, but the on-site conditions and available equipment do not always allow them, so actual pressure and flow rate values are usually below expectations. By studying the available literature [2,3,4,5] only partial solutions were found to the problem. It requires complex calculations to take into account all potential losses [1], but there is no time for time-consuming calculations in case of an accident [6]. As a solution a simplified calculation model was developed [1]. To facilitate and accelerate the calculations a modular simulation model was developed in Matlab/Simulink. The basic model can be easily expanded with additional elements if necessary. The subsystems of the simulation model are the following:

- mobile centrifugal pump
- standardized fire hoses
- adapters
- nozzle

The examined system consists of a fire pump, an adapter, a B type hose and 2 C type hoses as shown in Fig 1.

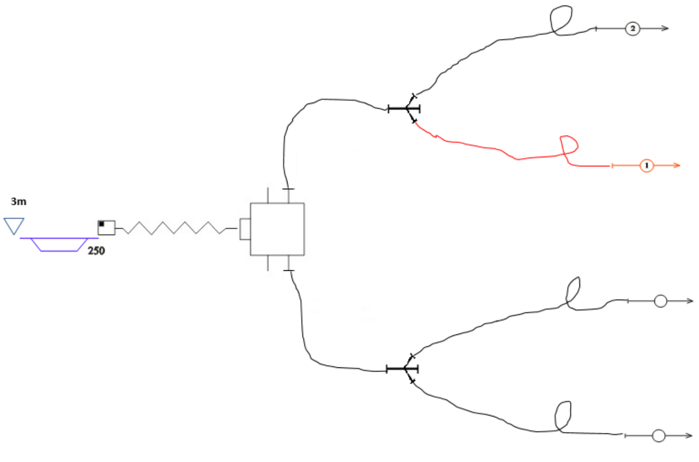

**Fig. 1.** Scheme of the examined firefighting system

The pump model was based a Rosenbauer Fox II type used in everyday practice in EU countries. The pump is powered from an underground water reservoir in suction mode. It was defined as an additional requirement for the firefighting system that the pump to provide the necessary amount of water and a pressure of 5 bar required for the operation of nozzles of DIN EN 15182-3 at a height of 10 meters. In order to meet our expectations a Q=0.00343 $m^3/s$ (206 l/min) flow rate should be provided at each water spray jet of the system. The diameter of the inlet is 52 mm and the diameter of the outlet is 12 mm of the nozzle. The length of the hoses all together is 40 m.

## 3. Simulation model

The simulation model was created in Simulink (Fig. 2). It is modular, easily expandable and made of subsystems.

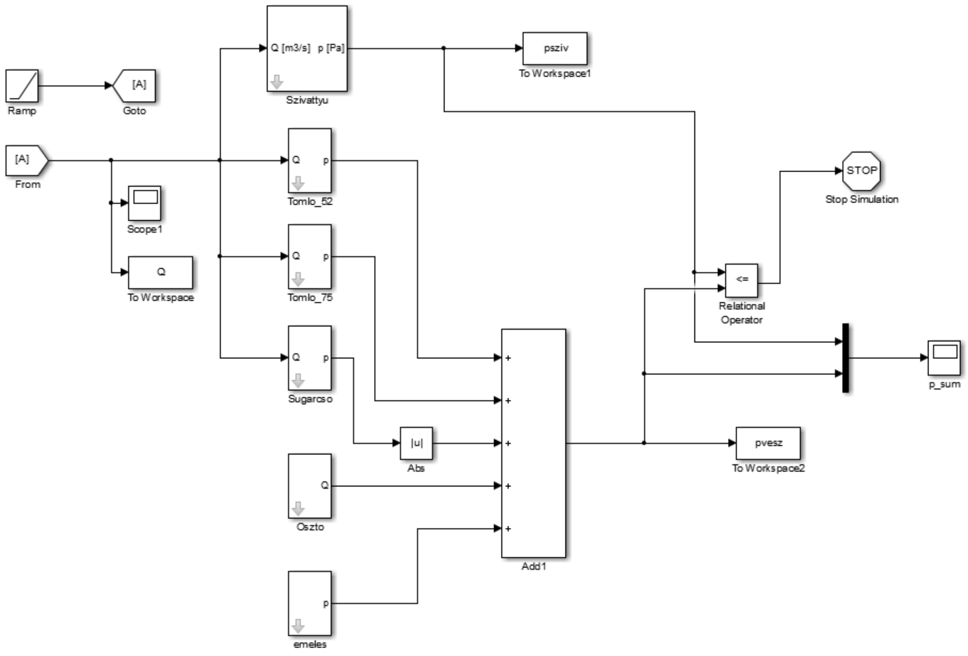

**Fig. 2.** Simulink model of the firefighting system

The subsystems are the following: pump, hoses, nozzle, adapter and lifting height. The subsystems are masked in order to change the parameters easily. The input variable is the flow rate and the output variables are the pressure of the pump (pressure side) and the total pressure loss in the system.

The pump subsystem is shown in Fig 3.

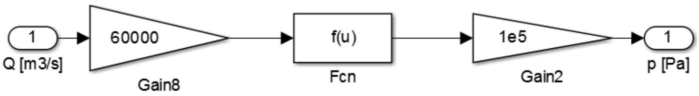

**Fig. 3.** Pump subsystem

The equation describing the subsystem is the following [1]:

$$p\,[bar] = n^2 \sqrt{1 - \left( i \frac{Q\,\left[\frac{l}{min}\right]}{2000} \cdot \frac{1}{n} \right)^2} \tag{1}$$

where *Q* is the flow rate, *p* is the pressure of the pump, *n* is the speed ratio compared to the maximum speed ($n_{max}$=4500 RPM) and *i* is the number of water spray jets. In the subsystem the speed ratio (n) and the number of water spray jets (i) are the variable parameters.

The pressure loss in the hoses can be calculated by the following equation [1]:

$$p_{hose} = c_d \cdot L \cdot (k \cdot Q)^2 \tag{2}$$

where $c_d$ is the proportionality constant depending on the diameter of the hose, *L* is the length of the hose and *k* is the number of hoses. The subsystem is shown is Fig 4.

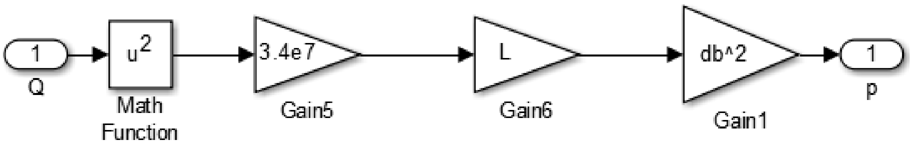

**Fig. 4.** Hose subsystem (C type)

The length (L) and the number of hoses (i) are the variable parameters. The diameter of the hoses was 52 (C type) and 75 mm (B type), which are standardized diameters. The proportional factor was only known for standardized hoses; therefore, the diameter of the hoses was constant in this study. In the future the diameter of the hose is also planned to be variable to test the systems behaviour in configurations different from the standardised hoses.

The pressure drop in the nozzle can be calculated with the following equation:

$$p_n = \frac{\rho}{2} \cdot \left( \frac{1}{A_1^2} - \frac{1}{A_2^2} \right) \tag{3}$$

where $\rho$=1000 kg/m$^3$ is the density of water, $A_1$ is the cross section at the inlet of the nozzle and $A_2$ is the cross section at the outlet of the nozzle. The cross section can be calculated with the following equation:

$$A = \frac{d^2}{4\pi} \tag{4}$$

From equations (3)-(4) the subsystem of the nozzle can be created (Fig. 5). A 96% efficiency is given in the standard, which is also taken into account.

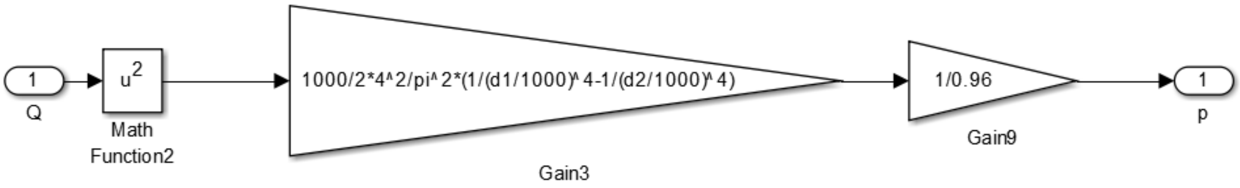

**Fig. 5.** Nozzle subsystem

The variable parameters of the subsystem are the inlet and outlet diameters.

The subsystem of the adapter is shown in Fig 6. According to literature the pressure drop in case of an adapter is 0.69 bar [7]. It has only a single variable parameter, which is the number of adapters.

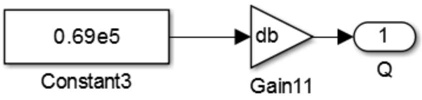

**Fig. 6.** Adapter subsystem

The subsystem of the lifting height is shown in Fig 7. Theoretically a 10 m height causes 1 bar pressure drop [2]. The height is the variable parameter.

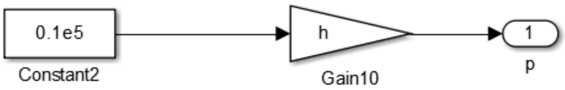

**Fig. 7.** Lifting height subsystem

## 4. Simulation results and parameter sensitivity study

First the pressure at the pump and the pressure loss in the system were calculated in case of the initial configuration (Q=3.43e-3 [$m^3/s$], i=4, n=0.78). The pressure can be seen in Fig. 8 left. It can be observed that the pressure at the pump is 6.8734e5 Pa and the pressure loss is 6.7989e5 Pa. The results are the same as calculated in [1]. There are only small differences in the pressure loss compared to the results of [1], because a slightly different nozzle model was used for easier testing and expandability. The model was then tested with increasing flow rate. The simulation was stopped, when the pressure loss was greater than the pressure at the pump (Fig. 8 right).

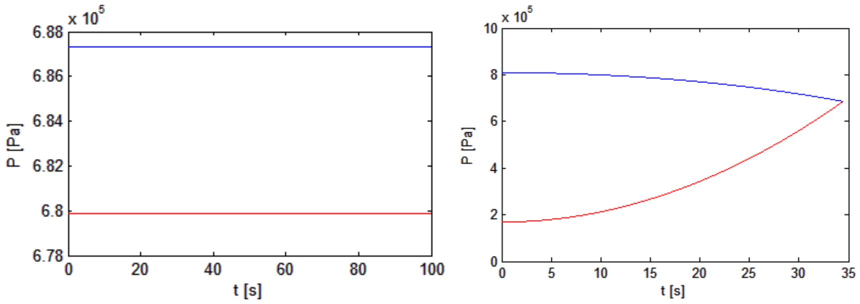

**Fig. 8.** Pressure in the original configuration (left) and increasing flow rate (right) (blue: pressure of the pump, right: pressure loss)

For sensitivity study the maximum flow rate which can be extracted in case of a configuration was selected. The flow rate was increased until the simulation stopped and the last value was stored in a list. Then the maximum flow rate versus the varied parameter was plotted in a diagram. From the diagrams the sensitivity can be measured with a sensitivity index, which can be calculated as follows:

$$SI = \frac{\Delta Q_{max}\ [\%]}{\Delta a\ [1\%]} \tag{5}$$

where *Δa* is the 1% change in the selected parameter. To measure sensitivity the following Fuzzy sets were established [8]:

- not sensitive: SI<=1
- moderately sensitive: 1<SI<=5
- sensitive: 5<SI<=10
- extremely sensitive: 10<SI

The parameter is considered sensitive, when there is a parameter range in the extremely sensitive or the sensitive Fuzzy set.

The sensitivity of the speed ratio and the lifting height are shown in Fig 9.

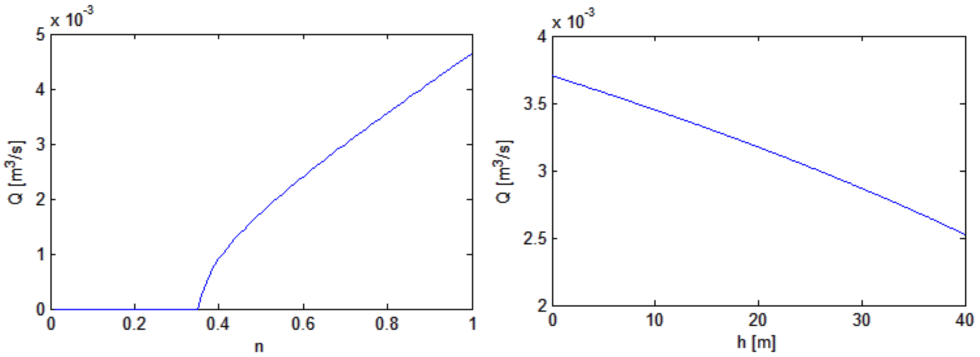

**Fig. 9.** Sensitivity of the speed ratio (left) and the lifting height (right)

The speed ratio is not sensitive when n<0.36. Till this speed ratio there is no fluid flow in the system. When 0.36<n<0.4 the parameter is extremely sensitive, SI=19.5. When 0.4<n $Q_{max}$ increases linearly. In this range SI=4.68, therefore the parameter is moderately sensitive.

The sensitivity of the lifting height changes almost linearly during the entire examination range. SI=0.3, therefore this parameter is not sensitive.

In Fig.10 the sensitivity of the nozzle inlet and output diameters are shown.

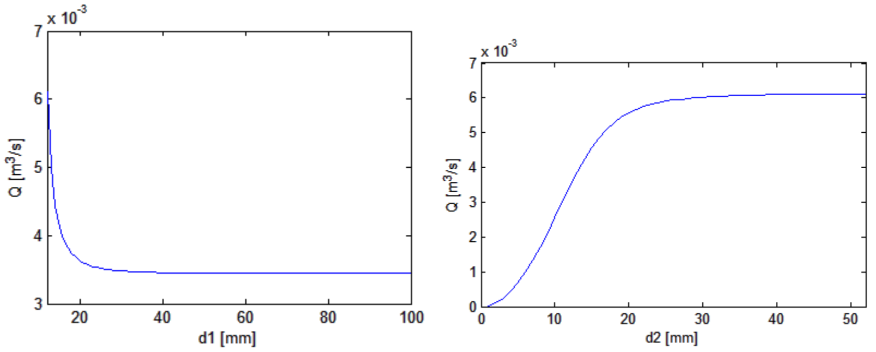

**Fig. 10.** Sensitivity of the inlet diameter (left) and the outlet diameter (right) of the nozzle

When the inlet diameter is small ($d_1$<10 mm) it is moderately sensitive with SI=2.667. When 10<$d_1$<22 mm it is not sensitive, SI=0.5. When $d_1$ is further increased the maximum flow rate remains the same, therefore this parameter is not sensitive. When the outlet diameter of the nozzle is small ($d_2$<4) it is moderately sensitive with SI=3.2. When 4<$d_2$<18 it is moderately sensitive (SI=4.33). When this parameter is further increased it is not sensitive (SI=0.17). It can be observed that the inlet diameter is more sensitive than the outlet diameter.

In Fig.11 the sensitivity of the hose lengths is shown.

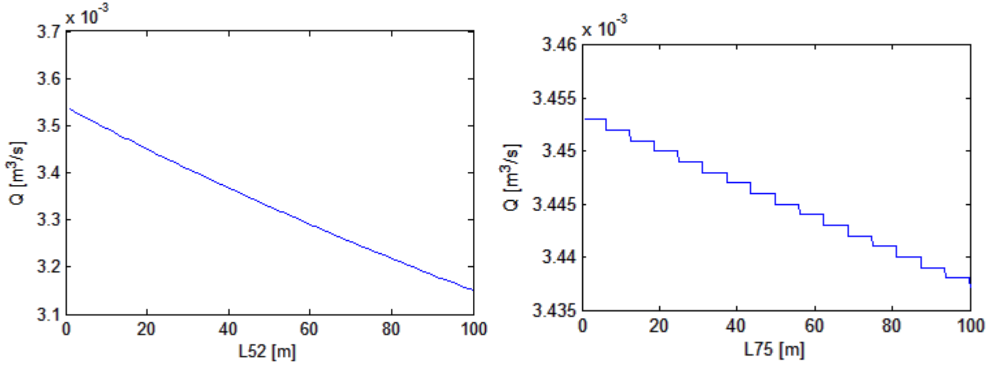

**Fig. 11.** Sensitivity of the hose length (left: C type, right: B type)

It can be seen that the maximum flow rate decreases almost linearly as the length of the hoses is increased. These parameters are not sensitive, $SI_{max}$=0.067 and $SI_{max}$=0.0026.

It can be concluded that the speed ratio of the pump is the most sensitive parameter, only it has range in the extremely sensitive Fuzzy set. All the other parameters are moderately sensitive or not sensitive. With this study it was proved that the examined firefighting system is well designed, there are no weak points. Except the speed ratio of the pump the parameter values are in the not sensitive range. With this study it was shown that the pump is the most critical element of the system. Therefore, an important further research task is to develop a pump model and carry out its sensitivity analysis in more detail.

## 6. Conclusions

In this study the operation parameters of a firefighting system were examined. In order to facilitate and accelerate calculations a modular, easily expandable simulation model was created in Simulink and numerical simulations were performed. Analyzing the results it can be concluded that in case of water spray jets operated in different system configurations there are differences in the maximum amount of water that can be extracted. It should be taken into account during firefighting tasks. It was also observed that significant pressure losses occur inside the system. With the simulation model the parameter sensitivity study of the subsystems was carried out. From the sensitivity study it was concluded that the pump is the most critical element, therefore in the future it will be further examined with more detailed simulation models and field measurements. All the other elements are moderately sensitive or not sensitive. Another research task is to expand the model further and examine other configurations as well. In the future using the model and numerical simulations, fire department exercises can easily be used to test assembled firefighting systems. Experience from the simulations can also be put into practice to avoid problems with water supply due to improper operation.

### Acknowledgments

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Innovációs és Technológiai Minisztérium

Új Nemzeti Kiválóság Program

This study was supported by the ÚNKP-19-3-III-SZE-11 New National Excellence Program of the Ministry for Innovation and Technology.

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