EPJ Web of Conferences **269**, 01068 (2022) https://doi.org/10.1051/epjconf/202226901068
EFM 2019

Mathematical simulation of the high capacity pumping system for emergencies

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Abstract. The article deals with the possibilities of mathematical simulation of the high-capacity pumping module used in emergencies, such as floods and fires. These situations can be broad and varied. In order to respond to these events effectively, formulation of methodology followed with simulation of various scenarios can be very helpful. Based on the high-capacity pumping module MČS-25-330-K produced by Sigma company, and the related certified methodology for its application in the field, mathematical simulations of the system were carried out in MATLAB Simulink. The discharge pressure, flow rate and the pressure loss through straight fire hoses were evaluated for various operational conditions of the pump and partly compared with the field measurement.

1 Introduction

The experience of the fire rescue units on domestic and foreign missions shows that in many cases of emergency respond (floods, flash floods, forest fires, fires in cities and in industrial areas, etc.) the long-distance transport of water is necessary. For this purpose, the high-capacity pumping module is required, providing the desired flow-rate and the pressure to cover the pressure losses through the fire hoses.

In the framework of the research project of the Ministry of the Interior of the Czech Republic (No. VG20132015111, "VYMOCERMIS", solved in 2013 - 2015), the prototype of the new high-capacity pumping module MČS-25-330-K, Sigma, was developed and tested in the field. The practical findings on field deployment of high-capacity pumping module for long-distance water transport were included into the following elaborated certified methodology “Operationally tactical instructions for field deployment of high capacity pumps for long-distance transport of water in emergencies”[1], (hereinafter referred to as Methodology). The intended users of this HCPM are primarily the intervening units of professional firefighters, namely the commanders of intervening units in emergencies.

The Methodology defines the basic procedures for the effective and safe deployment of the named high-capacity pumping module (hereinafter referred to as HCPM), as well as the technical and organizational requirements for its setting, start-up, operation and shut down.

Besides basic principles and guidance for the field deployment of HCPM, the methodology presents a tool for the estimation of the pressure loss in the hose line according to available professional sources and field measurements. The prevailing source in a long distance transport is friction and so the pressure loss through a straight hose is proportional to its length. In emergencies, where there is no time for complicated calculations, tables and graphs are used, which provide approximate results. Most often, pressure drop per 100m length of pipe (or hose) is defined, based on the pipe diameter and flow-rate.

For a long-distance water transport, the distance between the water source and the end site and the elevation between both sites will play an important role. These two values will significantly affect the requirements on pump pressure and flow-rate. The discharge pressure from the pump covers several purposes:

- create a water stream that can be a compact or shattered with the desired spray rate, the required minimum pressure in the nozzle conditions the formation of such a stream,
- overcome the frictional losses in the hose line as well as local losses in fittings,
- overcome the geodetic head between the water source and the fire site.

The Methodology [1] contains estimated pressure losses in fire hoses based on specified field conditions. As the data provided with the experimental measurement were limited, the main objective of this work was to extend the range of pressure loss determination for various operational conditions of the high-capacity pumping module (HCPM) using mathematical simulations in MATLAB Simulink.

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2 Field measurement and experimental investigation of pressure losses

Mobile high capacity pump module MČS-25-330 K, produced by Sigma company [3], consists of horizontal spiral pump A-200-KIDR-550, diesel engine Caterpillar C27 ACERT (783 kW, 1800-2100 rpm) and accessories placed on a steel frame, which is inserted into a floating container, adapted to be handled and loaded by a single-arm heavy-duty container carrier according to DIN 30722-1. The weight of the HCPM container with the power unit is about 10.5 t with a diesel tank. The weight of the hose container with 2 km of DN150 dispensing hoses including couplings is approx. 9 t.

The basic performance parameters of HCPM at BEP are as follows [3]:

- n = 1900 rpm, Q = 330 l/s (19 800 l/min), p = 16.5 bar, P = 645 kW.

For normal operation, the pump works at the speed range from 1400 to 1800 rpm, and from affinity laws the corresponding parameters are as follows:

- n = 1800 rpm, Q = 315 l/s (18 900 l/min), p = 14.5 bar, P = 547 kW
- n = 1600 rpm, Q = 280 l/s (16 800 l/min), p = 11.4 bar, P = 385 kW
- n = 1400 rpm, Q = 245 l/s (14 700 l/min), p = 8.8 bar, P = 258 kW

Recommended hoses diameter for the long-distance transport are DN150 (minimum), DN200 or DN250 (optimum).

Field experiment was carried out in 2015 and 2016 in Moravian-Silesian region. Fig. 1 shows simple scheme of HCPM MČS-25-330-K with suction and discharge system. Suction system includes suction humper, two parallel hoses DN250 with the length of 6m. Discharge part of pumping module consists of return valve, flow divider that enables distribution of water to one, two or three straight-line hoses and one backflow hose (for the potential testing of future hydrodynamic booster pump prototype).

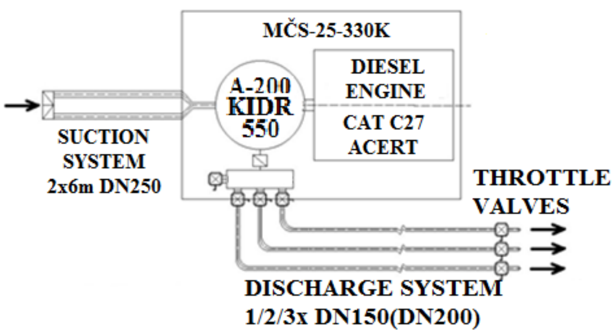

Fig. 1. Scheme of HCPM with suction and discharge system.

The field measurement considered two main scenarios [1]:

- Scenario 1 – long distance water transport for fire extinguishing. Pressure required at the end of the nozzle varies from 4 to 7 bar, single hose DN150 and parallel conduits of two and three hoses DN150 were considered.
- Scenario 2 – long distance water transport for drainage, required end pressure is assumed 0 bar, single hose DN150 and parallel conduits of two and three hoses DN150 were considered.

The main objective of the field experiment was to specify the maximum possible hose length in discharge part of pumping system in the range of defined flow and pressure conditions:

- Max. discharge pressure p_{max} =16 bar
- Pump speed: 1400, 1600, 1800 rev/min
- Pump flow rate: 60, 80, 100, 120, 140, 160, 180, 200, 220 l/s
- Number of pressure hoses in discharge system: 1, 2, 3
- Pressure at the end of hoses: 0, 4, 7 bar

From the results of the field measurement the optimum values of pressure, pump speed and potentially possible lengths of the hose line for the long-distance transport of water were calculated. Subsequently, the values were summarized and put into well-arranged tables and graphs in order to simplify as much as possible the necessary considerations for the optimal setting of the HCPM for possible emergency water scenarios.

3 Mathematical model of high capacity pumping system in MATLAB Simulink

Mathematical simulation of the whole hydraulic system enables to test various combinations according to the upper mentioned condition of field experiments [6,8]. In total, 177 combinations were developed and tested, that were partly compared with the data provided by the Methodology. The scheme of the system is illustrated in Fig.2.

The mathematical model is composed of following elements: centrifugal pump, resistive tubes and fixed orifices, which simulates end regulation valves or fire monitors within the model. Parameters of those elements significantly affect calculation results. Flow-rates and pressures that correspond to the Methodology [1] were determined through the combination of these parameters.

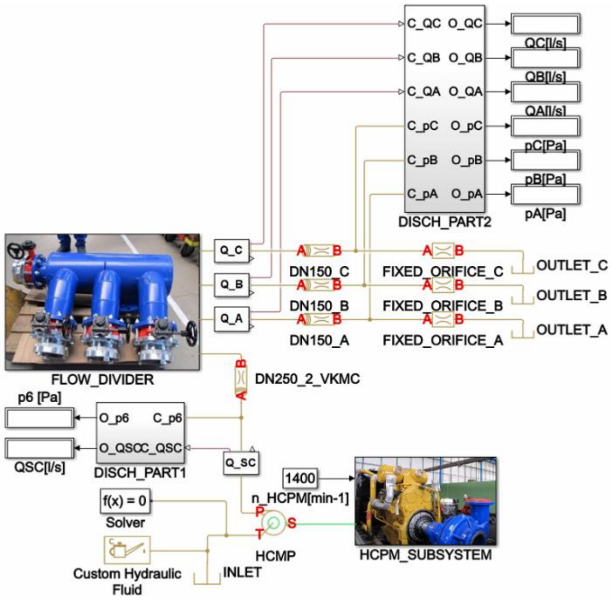

Fig. 2. Example of mathematical model of high-capacity pumping module setup in MATLAB Simulink.

4 Pressure drop calculation

Parameters of the modeled system affect searched maximum hose length. In practice, available power of HCPM is significantly affected by choice of type, length and DN of transportation rubber hoses. In case of DN150 hoses, this specific HCPM could be run only on 1/2 or 2/3 of its maximum available power.

In order to consider the result acceptable, it is necessary to monitor and control the flow rate and the pressure at the end of hoses. The end pressure p_A is given by the difference between the discharge pressure p_6 and pressure loss Δp (1).

$$p_A = p_6 - \Delta p \tag{1}$$

Pressure drop in the hose is given by

$$\Delta p = \rho g h_f = \rho g \left(\lambda \frac{l}{d} \frac{v^2}{2g}\right) \tag{2}$$

The average velocity v is determined from continuity equations for incompressible flow

$$v = \frac{4Q}{\pi d^2} \tag{3}$$

$$\Delta p = \rho g \left(\lambda \frac{8l}{\pi^2 d^5}\right) Q^2 \tag{4}$$

Friction factor λ is calculated based on the regime of water flow in a hose. For turbulent flows we assume $Re >= Re_T$, where minimal value of Reynolds number is $Re_T = 4000$. Friction factor λ is calculated according to Colebrook-White formula in MATLAB Simulink [2].

$$\lambda = \frac{1}{\left[-1{,}8 log\left(\frac{6{,}9}{Re} + \left(\frac{k}{3{,}7d}\right)^{1{,}11}\right)\right]^2} \tag{5}$$

The end pressure in discharge system is determined by the definition of the “fixed orifice”. It is possible to set up orifice area A, flow discharge coefficient C_D, laminar transition specification and laminar flow pressure ratio as depicted in Fig.3.

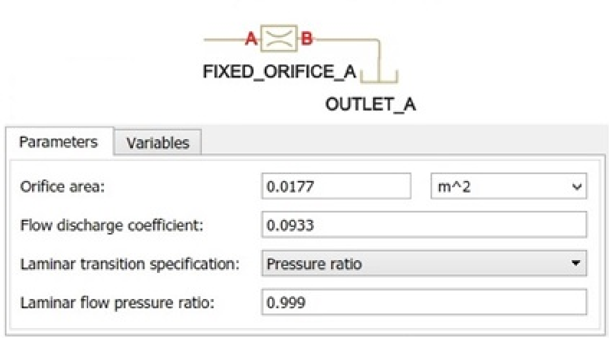

Fig. 3. Fixed orifice setup in MATLAB Simulink [2].

Roughness height on the pipe internal surface was determined as 0.00003m [2]. Flow-rate in fixed orifice was calculated from equation (6),

$$Q = C_D . A \sqrt{\frac{2}{\rho}} . \frac{p}{(p^2 + p_{crit}{}^2)^{1/4}} \tag{6}$$

where

C_D Flow discharge coefficient [-]
Q Flow-rate [m^3/s]
A Orifice passage area [m^2]
ρ Fluid density [kg/m^3]
p_{crit}- Minimum pressure for turbulent flow [Pa]
p Pressure differential p_A-p_B

Minimum pressure for turbulent flow is calculated from equation (7).

$$p_{crit} = \frac{(p_{avg} + p_{atm})}{(1 - B_{lam})} \tag{7}$$

where,

p_{avg} Average pressure between the block terminals $p_{avg} = (p_A + p_B)/2$
p_{atm} Atmospheric pressure 101325 Pa
B_{lam} Pressure ratio at the transition between laminar and turbulent regimes. The default value is 0.999.

5 MATLAB Simulink solution method applied for the case of HCPM

Equations (1)-(7) contain constants and variables that are possible to use on the debugging of pumping system model within the MATLAB Simulink software [2]. The pumping system model was debugged with respect to required pressure and flow values [4]. This process was implemented through the step by step change of the hose length and flow discharge coefficient. The simulation is possible to solve with automatic script or with manual setting. Automatic solution requires fixed and fine iteration step for length and discharge flow coefficient. It leads to a large number of iterations. Figure 4 shows script flowchart for automatic solution.

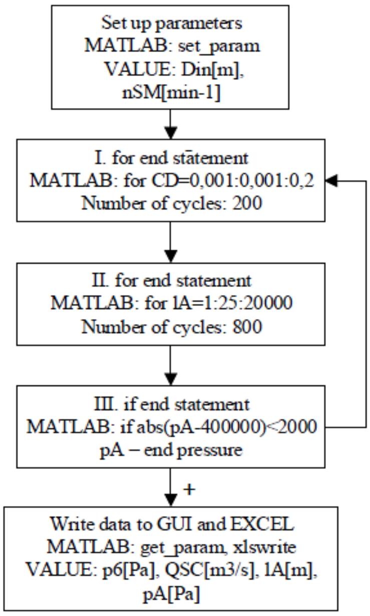

Fig. 4. Script flowchart of automatic solution mathematical model.

It is more advantageous to solve the simulation with manual setting by GUI (graphic user interface). Manual solution allows to skip several combination of C_D and l that are very distant from estimated right solution. Solution accuracy was set to the end pressure ±2000Pa and flow rate ±0.15 l/s. Figure 5 shows graphic user interface for manual setting.

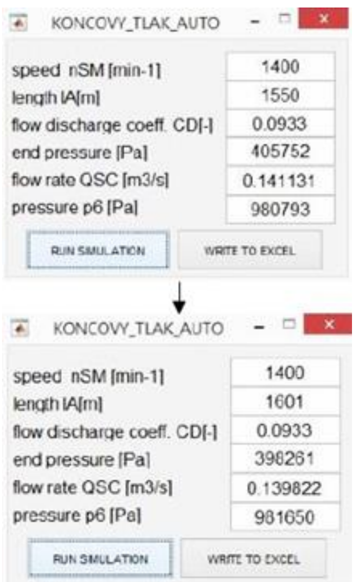

Fig. 5. Manual setting of slx file using MATLAB GUI.

The main goal of the calculation was to define maximal useful length of hoses for defined pump speed, flow-rate and required end pressure. The obtained data were compared with those presented in Methodology and are presented in Tab 1 for one hose DN150.

Table 1. Maximal pipe length determined with Methodology and in MATLAB Simulink.

SPEED n [min-1]	FLOW R Q [l/s]	METH. l1 [m]	MATL. l2 [m]	DIFF. l2-l1 [m]	DEV. [%]
1400	60	1038.4	1040.6	2.2	0.21
1600	60	1726.9	1573.1	-153.8	8.91
1800	60	2302.6	2176.9	-125.7	5.46
1400	80	647.6	592.4	-55.2	8.52
1600	80	971.4	901.4	-70	7.21
1800	80	129.2	1248.1	-47.1	3.64
1400	100	414.5	378.7	-35.7	8.61
1600	100	621.7	578.5	-43.2	6.95
1800	100	828.9	805.4	-23.6	2.85

The result of maximal length from Methodology [1] and mathematical modelling were compared only with each other. Deviation between these two lengths was calculated by equation (8).

$$deviation\ [\%] = \frac{100\%.Abs(l_1 - l_2)}{MAX(l_1;l_2)} \tag{8}$$

The smallest deviation from all simulation was 0.12% and the highest deviation was 27.33%. Maximal length calculated with mathematical modelling are smaller than values from field deployment methodology. Difference is negative in this case.

6 Differences and evaluation between the Methodology and MATLAB Simulink calculation

The maximal hose length is affected with the discharge pressure p_6 behind the pump and pressure loss in the hose system. The discharge pressure p_6 was used to determine the loss head (9).

$$h_f = \frac{p_S}{\rho g} = \frac{p_6 - p_A}{\rho g} \tag{9}$$

In the Methodology [1], the discharge pressure was approximated from the pump curves at various pump speed and was considered constant in specified range of the flow-rate (Fig.5), while in MATLAB [9] the discharge pressure was calculated with higher accuracy from the vector function p-Q (see Tab. 2). Pressure p_A is the end hose pressure fixed to 4 or 7 bar in case of fire extinguishing and zero in case of drainage.

The second difference was in determination of friction losses in the hose line. The field Methodology defines the resistance constant k based on constant value of friction coefficient λ, which does not account for the dependence on Reynolds number.

$$h_f = kQ^2 \tag{10}$$

$$k = \lambda \frac{8l}{\pi^2 d^5} \tag{11}$$

MATLAB Simulink defines friction factor according to Colebrook-White equation (5). Table 2 and 3 shows the comparison of friction factor calculated in methodology and mathematical modelling.

Table 2. Comparison of pressure p_6, loss head for MATLAB and field deployment methodology.

SPEED [min-1]	MATL. p6[bar]	METH. p6[bar]	MATL. hz[m]	METH. hz[m]
1400	10.01	10	62.23	62.09
1600	13.09	13	94.07	93.15
1800	16.58	16	130.18	124.19
1400	9.95	10	61.63	62.09
1600	13.06	13	93.78	93.14
1800	16.55	16	129.85	124.19
1400	9.87	10	60.71	62.09
1600	12.96	13	92.72	93.14
1800	16.47	16	129.09	124.19

Table 3. Comparison of friction factor for MATLAB and field deployment methodology.

- v[m/s]	- Re[-]	MATL. λ[-]	METH. λ[-]
3.53	509296	0.01527	0.01377
4.71	679061	0.01494	0.01377
5.88	848826	0.01473	0.01377

Figures 6, 7, 8 illustrate the comparison between field deployment methodology and mathematical modelling for one hose DN150 and parallel connection of two and three hoses DN150. It can be observed that for the same value of the loss head the flow-rate predicted by MATLAB Simulink is lower in comparison with the methodology.

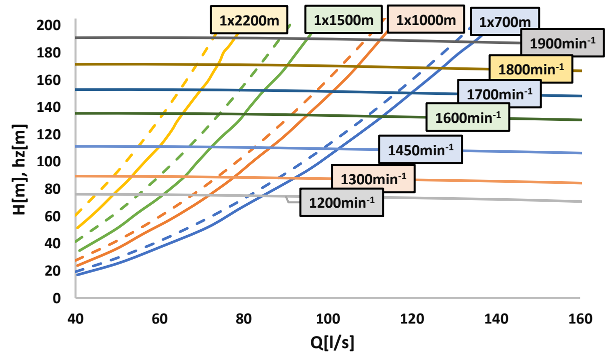

Fig. 6. Pipeline characteristics for 1xDN150 - 700, 1000, 1500, 2200 m (solid line – Methodology, dashed line – MATLAB).

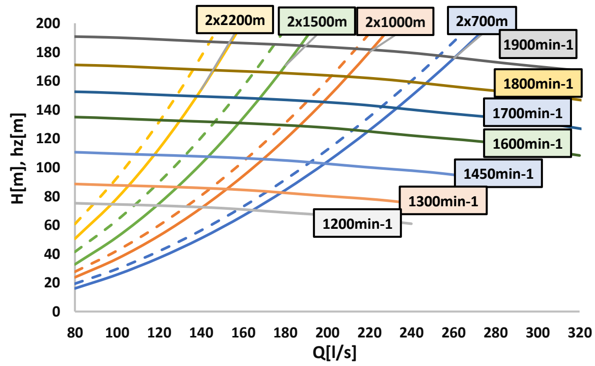

Fig. 7. Pipeline characteristics for 2xDN150 - 700, 1000, 1500, 2200 m (solid line – Methodology, dashed line – MATLAB).

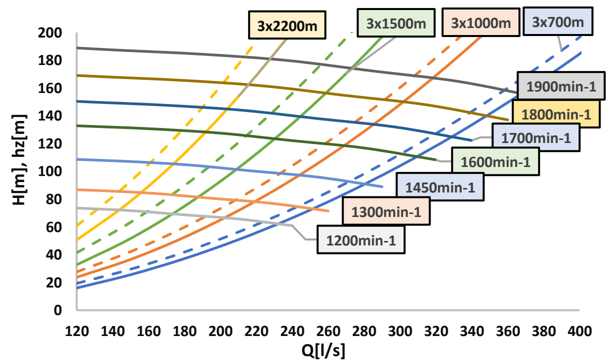

Fig. 8 Pipeline characteristics for 3xDN150 - 700, 1000, 1500, 2200 m (solid line – Methodology, dashed line – MATLAB).

7 Model uncertainties & simplifications

The mathematical model always represents only a partial replacement and simplification of the real model [6, 8, 9]. In practice, there can always be factors that the mathematical model does not take into account. The purpose of creating a mathematical model is to get as close as possible to reality. The field experiments are very difficult in term of time, finance, staff or safety. Therefore, it is very advantageous to solve HCPM problem with mathematical modeling based on the field experiment. There were several simplifications in HCPM model that could affect the final results. First, the suction system with a length of 6m was neglected. This omission has minimal effect on final result. The pressure loss in flow divider and another elements (couplings) in HCPM setup were also neglected with respect to prevailing friction losses. These minor pressure losses could be more significant. If the pressure loss in the flow divider was included in the calculation, the maximum stated length of hoses would be even lower. It would be useful to determine pressure loss in atypical flow divider by measurement or numerical modelling in CFD software.

8 Conclusion

The firefighters, namely the commanders of intervening units in emergencies, are facing many decisions that must be done rapidly, with high responsibility. Prepared scenarios with corresponding instructions can be the useful tool in emergency situations. Field measurement is the most common approach for obtaining the necessary data, but enables to investigate only limited range of conditions, under lower accuracy and high uncertainties. Operation of HCPM is affected by many parameters, the combination of which cannot be experimentally tested in the whole range. For this purpose, mathematical modelling can be applied to create a large volume of useful data as the background for preparing available tables and graphs. Estimation of pressure losses in long distance transport is very important. Differences between the field deployment Methodology and mathematical modelling were evaluated. Resulting hose line characteristics determined in Methodology and mathematical modelling show good agreement, however the pressure losses predicted in MATLAB Simulink are higher than those determined in Methodology.

In some situations, for fully effective utilization of HCPM, it is necessary to overcome the geodetic head between the water source and the fire site. The HCPM pump A-200-KIDR-550 requires the specified minimum suction pressure to avoid the cavitation causing the loss of pressure, efficiency and erosion of pump internals. The booster pump will increases the pressure of water so that the required suction pressure is ensured. For these purpose two booster pumps will be used together with HCPM that are currently under development in Sigma Company. The next work will be focused on mathematical simulation of HCPM operating with boosters.

The article was supported by project No. VI20152019030 "Research and development of a booster pump for high-performance pumping sets" (acronym: PAHDE), supported by the Ministry of the Interior of the Czech Republic for solution within the period 2015 - 2019.

This work has been supported by The Ministry of Education, Youth and Sports of the Czech Republic from the Specific Research Project SP2019/123 (Numerical Modeling of Dynamic Phenomena in Fluid Mechanics with Support of Experimental Research).

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