Modelling and Simulation of Hydraulic Pipe Networks using Matlab /Simulink / Simscape

Gérémino Ella Eny, Honorine Angue Mintsa Eya, Gamany Luthenda, Abbas Aouissi

Abstract— **Designing urban water supplies poses one of the greatest challenges in the modern world for fluid mechanics engineers. In academia, the Microsoft Excel Hardy Cross method (MEHCM) is widely used for solving hydraulic pipe network problems. In this paper, an alternative method is proposed using the Simscape library in the Matlab/ Simulink environment. The approach is compared to the MEHCM. We focus on the flow calculations of two sources to supply a hydraulic pipe network with four desired demand flow rates. First, the pipe network is built using different components available in Simscape / fluids library block. Next, the value of the different hydraulic resistance pipes, head elevations of the nodes and the desired flow demands are specified in the components. Since hydraulic resistances include pipe inside diameter, length and coefficient of friction, we reorganize the Simscape pipe component settings. Then, the simulation is run while we use excel spreadsheets calculations to solve MEHCM. The obtained results show that the proposed Simscape implementation gives good results with a saving of time while the MEHCM in excel involves several laborious iterations. Futhermore, in order to anticipate real-time implementation problems, we simulate the case study where the demand nodes are open freely. Here again, the proposed method offers the possibility of analysing the problem of hydraulic pipe networks after real-time implementation.**

Index Terms— **Hardy Cross Method, Matlab Simscape, hydraulic pipe network, Excel spreadsheet calculation.**

I. Introduction

Getting a fluid to a starting point to an ending point by satisfying pressure and flow conditions is one of the main responsibilities of a fluid mechanics engineer. The task complexity increases when it comes to supply various demand points at various topographies including different hydraulic gradient levels. The water supply and distribution pipes network include water supply points, water demand points, pipes, fittings, etc [1]. Control devices are also needed for leakage detection [2], pressure detection [3] at different locations. Water supply points may be a elevated tower water [4] or pumps[5]. It can be a question of supplying various demand points in a buiding [6] or various demands points in a city [7].

In the academic literature, Hardy Cross (HCM) is the main approach used to design these hydraulic pipelines networks[8] [9] [10]. First, a physical model of the pipeline network configuration is drawn where the location of the demand points, the source points are identified. The characteristics of the hydraulic pipes and the desired flow demands are known. The pipeline network configuration may have a looped form [11], a branched form[12] or the two forms [5]. Next, the flow value of each pipe is assumed while satisfying the node continuity equation. Then, using the head loss sum equation, a correction flow in each loop is found. The approach is iterative in order to obtain the cancellation of the head loss algebraic sum in each loop. Because the number of iterative calculations may be enormous, some authors modify the original HCM with mathematical tools [9] to accelerate the convergence. However, the number of iterations of the modified HCM and the one of original HCM are almost the same [13].

In the past, HCM calculations may be done manually and then using Fortran programmation [8] [14]. Nowadays, engineers use solvers like excel spreadsheet [15], Matlab [16] to execute the HCM. Network pipe modelling softwares like Epanet are used to facilitate the design and the analysis of the pipeline network [17]. The software Matlab Simulink shows good results in the analysis of gaz pipelines networks [18]. More recently, the Simscape librairy of Matlab / Simulink is used to analyse a hydraulic network [19] to compare three types of pumps.

In this paper, we design and analyse a two-loop water pipeline network with two sources and four demands using the environment Matlab/ Simscape. The study objective is to determine the flow required by the two sources to supply the four consumption points at desired flowrate. The results are compared to those obtained by the HCM. The research goal is to offer an alternative learning method that is easier to construct and to analyze.

II. Problem statement

The hydraulic pipe network under study is the one presented in example 8.3 in [20]. It consists of two looped networks with four demands, two sources and seven pipes. Figure 1 shows the configuration of the network with the different head elevation and the desired flow demand at junction. The hydraulic pipe resistances are tabulated in table 1.
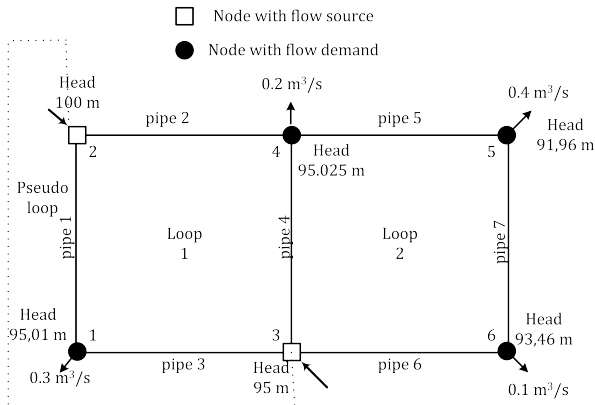
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Fig. 1: *Pipe water network configuration*

Table 1. Title of the table used for exemplification

Pipe	hydraulic resistance R (s^2/m^5)
1	40
2	20
3	10
4	30
5	40
6	20
7	50

III. HYDRAULIC PIPE NETWORKS GOVERNING EQUATIONS FOR STEADY FLOW

In this section, the two governing equations of the flow in a steady state are presented. The first one is the mass connservation in each node. The sum of the flow entering into the node equals the sum of flows leaving the node. Equation (1) shows the mass conservation for the incompressible fluid where Q_{input} .and Q_{output} are the flow entering and the flow leaving the node respectively.

$$\left(\sum Q_{input} - \sum Q_{output} \right)_{node\_i} = 0 \qquad (1)$$

The second governing equation is the conservation of the energy (2). For a real fluid (with friction), Bernoulli states that the variation of the total energy between two points equals the energy lost by the head loss h_{loss} .

$$\left[\frac{P}{\gamma} + \frac{V^2}{2g} + z \right]_1^2 = h_{loss\_1\_2} \qquad (2)$$

Where P is the fluid pressure, γ the specific weight, V the flow velocity, g the gravitational acceleration, the height. For a closed flow path, the equations (2) gives

$$\left[\sum h_{loss} \right]_{closed\_path} = 0 \qquad (3)$$

There exist several equations for the head loss in the literature references. For this paper, we use the exponential equation (3)

$$h_{loss} = RQ^2 \qquad (4)$$

IV. HARDY CROSS METHOD

In this section, the Hardy Cross method is applied to the hydraulic pipe network under study. We bring some variations from the solution presented in [20].

(1) Initial flowrate and their directions assumptions. The first step of the HCM is to assume pipe flowrate initial values. These values must satisfy the mass conservation principle at each node. Before attributing each flowrate at each pipe, we identify the positive direction in each loop as the clockwise sense.

(2) Algebraic sum of the head loss in each loop . In the second step of the HCM, the head loss of each pipe are calculated using the equation (3). According to the direction of the flow, a sign is put in the value of head loss. Then, the algebraic head loss sum are calculated for each loop. Then, we obtain

$$\left[\sum h_{loss} \right]_{closed\_path} = \left[\sum R|Q|Q \right]_{closed\_path} \qquad (5)$$

(3) Flow differentiating sum of the head loss in each loop . In the third step of the HCM, the first order Taylor series of each head loss are calculated according to the equation (6).

$$\frac{dh_{loss}}{dQ} = 2RQ \qquad (6)$$

The sign of each sum term is positive.

(4) Flowrate correction in each loop . In the fourth step of the HCM, the flow correction in each loop is calculated using the equation (7).

$$\Delta Q_c = -\frac{\sum RQ^2}{\sum |2RQ|} \qquad (7)$$

This flow correction is added to all the pipe flows belonging to the loop. The first iteration is done as is shown in Figure 2 with the corrected flow. For next iterations, we start again from step 1. The procedure is finished when the corrected flow becomes very small(i.e. $\sum RQ^2 ; 0$).
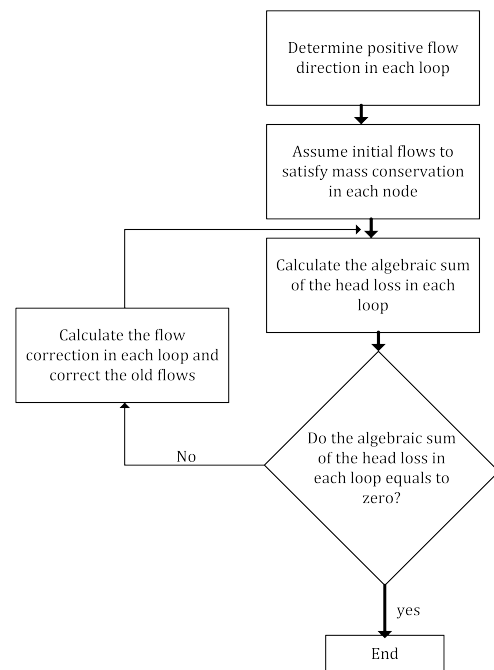

Fig 2: Flowchart of Hardy Cross method

Here, we only present the two first iterations implemented in the solver Microsoft excel. In table 2, 3 and 4, the first iterations in the three loops are completed. The first column is the number of the pipe. The second column shows the hydraulic resistance constant of each pipe. The estimated

flows in the third column are obtained by satisfying the mass conservation law in each node while the fourth column represents the sign flow in each pipe. The head loss values are calculated in the fifth column in order to obtain the algebraic sum in the seventh line. The flow derivative of the head loss expression are calculated in the sixth column with the sum presented in the eight line. The corrected flow is shown is the last line.

Table 2. Iteration 1 for loop 1

Loop 1					
Pipe	R	Q_{est}	Q sign	Sign.RQ^2	2RQ
1	40	0,35	-1	-4,9	28
2	20	0,45	1	4,05	18
3	10	0,05	-1	-0,025	1
4	30	0,05	-1	-0,075	3
ΣRQ^2				-0,95	
$\Sigma|2RQ|$					50
ΔQ	0,019				

Table 3. Iteration 1 for loop 2

Loop 2					
Pipe	R	Q	Q sign	RQ^2	2RQ
4	30	0,05	1	0,075	3
5	40	0,3	1	3,6	24
6	20	0,2	-1	-0,8	8
7	50	0,1	-1	-0,5	10
ΣRQ^2				2,375	
$\Sigma|2RQ|$					45
ΔQ	-0,052777778				

Table 4. Iteration 1 for the pseudo loop

Loop 3					
Pipe	R	Q_{est}	Qsign	RQ^2	2RQ
1	40	0,35	1	4,9	28
3	10	0,05	1	0,025	1
pseudo pipe				-5	
ΣRQ^2				-0,075	
$\Sigma|2RQ|$					29
ΔQ	0,002586207				

Table 5. Iteration 2 for loop 1

Loop 1					
Pipe	R	Q_{corr}	Q_{sign}	RQ^2	2|RQ|
1	40	-0,33359	-1	-4,45119	26,6869

2	20	0,469	1	4,39922	18,76
3	10	-0,03359	-1	-0,01128	0,671724
4	30	0,021778	1	0,014228	1,306667
ΣRQ^2				-0,04902	
$\Sigma|2RQ|$					47,42529
ΔQ	0,001033678				

Table 6. Iteration 2 for loop 2

Loop 2					
Pipe	R	Q_{corr}	Q_{sign}	RQ^2	2RQ
4	30	-0,02178	-1	-0,01423	1,306667
5	40	0,247222	1	2,444753	19,77778
6	20	-0,25278	-1	-1,27793	10,11111
7	50	-0,15278	-1	-1,16705	15,27778
ΣRQ^2				-0,01446	
$\Sigma|2RQ|$					46,47333
ΔQ	0,000311138				

Table 7. Iteration 2 for the pseudo loop

Loop 3					
Pipe	R	Q	Qsign	RQ^2	2RQ
1	40	0,333586	1	4,45119	26,6869
3	10	0,033586	1	0,01128	0,671724
pseudo				-5	
ΣRQ^2				-0,53753	
$\Sigma|2RQ|$					27,35862
ΔQ	0,019647532				

V. MATLAB/ SIMULINK: SIMSCAPE IMPLEMENTATION

In this section, we implement the hydraulic pipe network in the Matlab Simscape envionnement.

(1) The first step consists of constructing the hydraulic network using the module block in Simscape. The Figure 3 shows the different components used especially the hydraulic resistive pipe with variable elevation. The demand nodes are represented by a flow rate source that allows to fix the flow consumption. The source node are represented by hydraulic tank. Figure 4 shows the flowrate sensors.
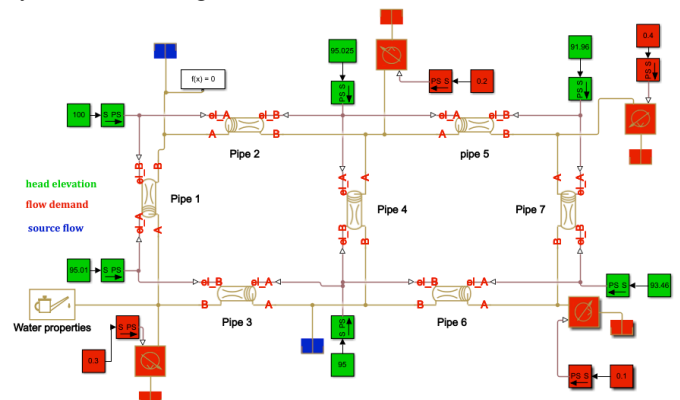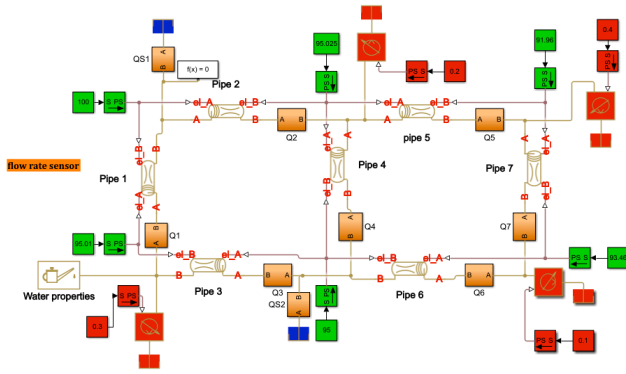
Fig 3: Hydraulic pipe network in Simscape

Fig 4: Hydraulic pipe network in Simscape with flow rate sensor

(2) In the second step, the hydraulic resistance is tuned in pipe. The hydraulic resistance h in Simscape block is calculated according to the equation (8).

$$h = f \frac{8\left(L + L_{eq}\right)}{\pi^2 g D^5} Q^2 \qquad (8)$$

Where f, L, Leq, D and Q are the friction coefficient, the pipe length, the pipe equivalent length, the inside diameter and the flow respectively. In order to put the required hydraulic resistance in the simulated pipe, the length pipe is initialized. We use a pipe simulation module initialisation as is shown in Figure 5. In the hydraulic pipe block caracteristics tube length of the Figure 7, we put the formula (8) in order to obtain $h = Q^2$ that is $R = 1$. The flow input used for the initialization module depends on the scale of the flow demands. In others words, we want to have an approximation of the friction coefficient.
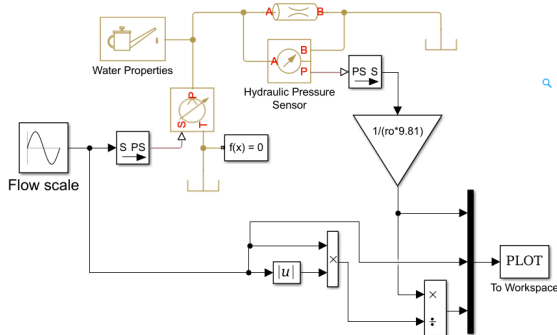

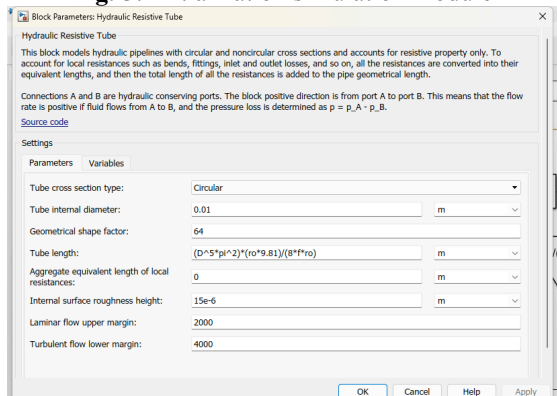**Fig. 5:** Initialization simulation module

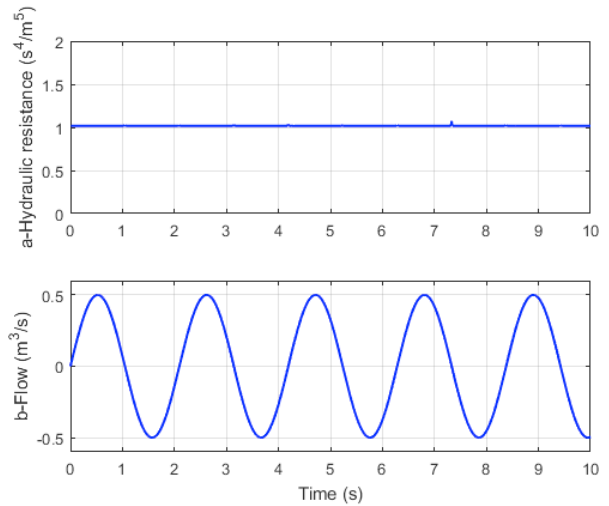**Fig. 6**: Hydraulic resistive pipe parameters for initialization

Fig 7: a-initialization of the hydraulic resistance in the pipe for the b-different flow demands

(3) The third step of this implementation is to put the different hydraulic resistance in pipes according to the problem statement as shown in Figure 8.
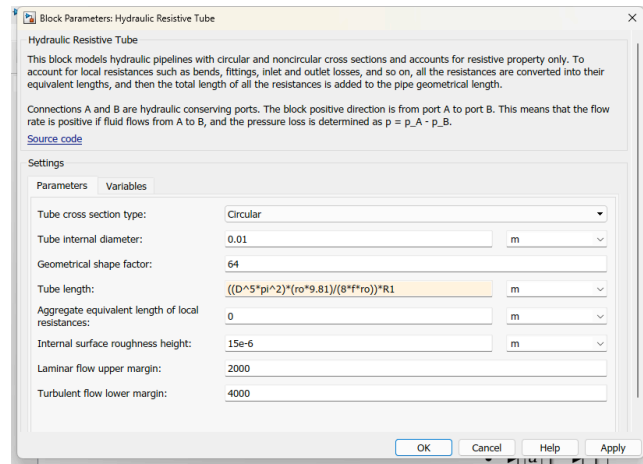

Fig. 8: Adding the hydraulic resistance in a pipe

VI. RESULTS AND COMMENTS

In this section, four results are presented. The Hardy Cross method results are obtained using the excel solver results. The Simscape implementation results are obtained by numerical simulation during 5 seconds. In the third subsection, the comparison between the two preceding approaches is discussed. The last result shows the demand flow nodes when implementing the source flows with pumps.

A. Results of Hardy Cross Method

After 36 laborious iterations, we obtain negligible corrections flows ΔQ as shown in Table 8, Table 9 and Table 10.

Table 8. Iteration 36 for loop 1

Loop 1					
Pipe	R	|Qcorr|	Qsign	RQ²	|2RQ|
1	40	0,353	-1	-4,97232	28,206

2	20	0,497	1	4,931388	19,862
3	10	0,0526	-1	-0,02764	1,051469
4	30	0,048	1	0,068575	2,868628
ΣRQ^2				1,83E-06	
$\Sigma \lvert 2RQ \rvert$					51,988
ΔQ	-3,51738E-08				

Table 9. Iteration 36 for loop 2

Loop 2					
Pipe	R	$\lvert Qcorr \rvert$	Q_{sign}	RQ^2	$\lvert 2RQ \rvert$
4	30	0,04781	-1	-0,06858	2,868628
5	40	0,248747	1	2,475004	19,89977
6	20	0,251253	-1	-1,26256	10,05012
7	50	0,151253	-1	-1,14387	15,12529
ΣRQ^2				-3,8E-06	
$\Sigma \lvert 2RQ \rvert$					47,9438
ΔQ	7,92054E-08				

Table 10. Iteration 36 for the pseudo loop

Loop 3					
Pipe	R	$\lvert Qcorr \rvert$	Q_{sign}	RQ^2	$\lvert 2RQ \rvert$
1	40	0,352573	1	4,972322	28,20588
3	10	0,052573	1	0,02764	1,051469
pseudo				-5	
ΣRQ^2				-3,9E-05	
$\Sigma \lvert 2RQ \rvert$					29,25735
ΔQ	1,32379E-06				

For each loop, one can see that the algebraic sum of the head loss is not equal to 0. The obtained value is smaller than 4×10^{-5} and we consider that this value significantly approaches 0 to stop iterations. Then, the flow required at source nodes using mass conservation equation are calculated and presented in table 11.

Table 11. Flow at source nodes

Source node	Q
2	0.85 m³/s
3	0.152 m³/s

B. Results of the Simscape implementation

In this section, the results obtained using matlab simscape are presented. The simulation is executed during 5 seconds and the sampling time is 10 ms. Figure 9 shows the pipe flowrates Qn and the source flowrates QSn according the conventional sign shown in Figure 4.
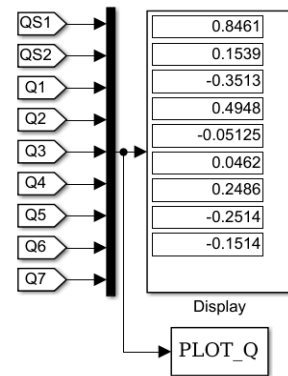

Fig. 9: Flowrates obtained after 5seconds of simulation

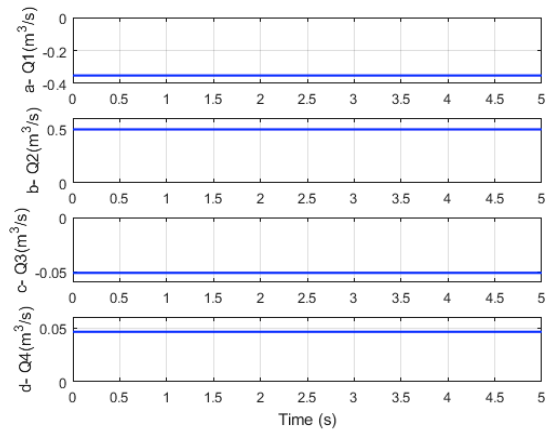Figures 10 to 12 show that the steady state flow values are obtained in less than 5 seconds.

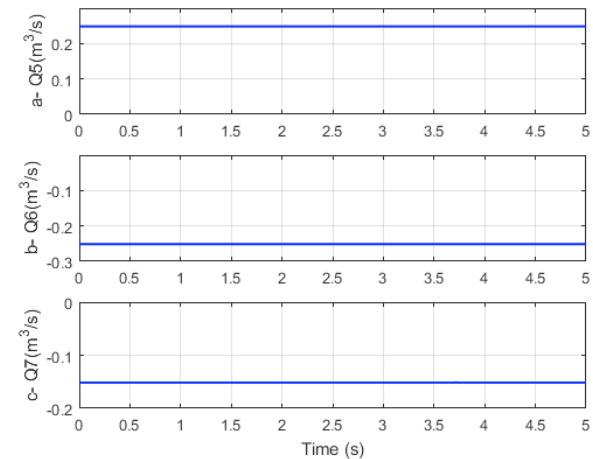**Fig 10:** Flowrates in pipe 1,2,3 and 4
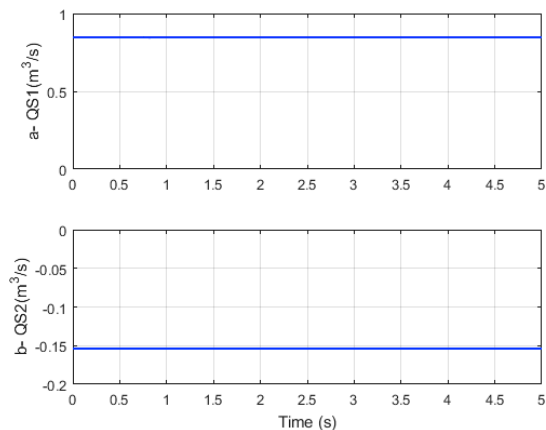

Fig 11: Flowrates in pipe 5,6 and 7

Fig 12: Source flowrate at a- node 2 and b- node 3

Figure 13 shows the result of the algebraic sum of the pressure loss in each loop. The attributed signs depend on the sign of the flowrate according to Figure 9. In the loop 1, the algebraic sum of the pressure loss is about 1×10^{-4} for the two loops.
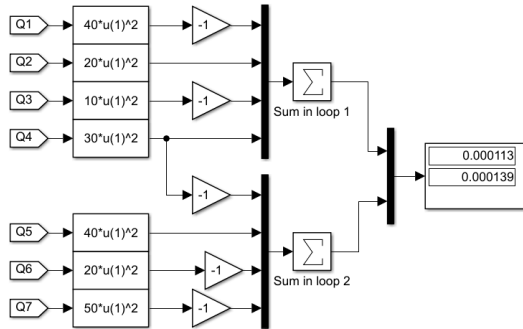

Fig 13: Algebraic sum of pressure loss in each loop

C. Comparison of the two methods

In the Hardy Cross method, we assume the initial value of the hydraulic pipe flows by satisfying the mass conservation equation at each node. In the matlab simscape method, we construct the physical network by initialising and putting the hydraulic resistance values at each pipe. The initialising step of the two approaches shows tuning values with the same difficulty. In the Hardy Cross method, the iterations are numerous and laborious in order to reach accurate results. The corrected flow sign in the new iteration is verify at each iteration while it only consists of executing the simulation in the matlab simscape approach. The results are obtained under 5 seconds. However, the algebraic sum in the case of the matlab Simulink approach is sum is about 10^{-4} while the algebraic sum is about 10^{-5} in the HCM.

The HCM makes it difficult to analyse the hydraulic pipe network. Because the approach is executed offline, the slightest variation that occurs when implementing often generates the restart of the approach. In the other side, the matlab simscape approach allows quick implementation tunings by varying flow demand or hydraulic pipe resistances. This advantage is helpful when simulating all the hydraulic pipe networks like leakage, dilapidated pipes etc.

D. Flow source pump analysis

In this section, we reproduce the real conditions of the hydraulic pipe network implementation using Matlab Simscape. The fix hydraulic flow rate sources at demand nodes are suppressed. In each source node, a flow rate source is put according to the solutions found in section 6.2. The objective of this simulation is to show the water distribution in each demand node. Figure 14 presents the implementation of the two sources by introducing 2 hydraulic pumps. Figure 15 shows that the flows at node demand correspond to the desired flow.
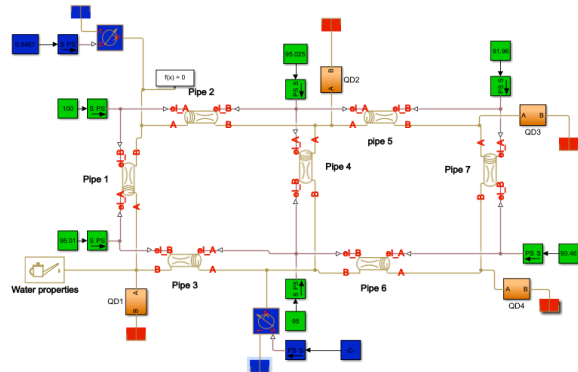

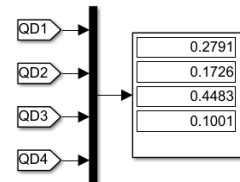**Fig 14:** Implementation of the two flow sources

Figure 15: Flow demand results

VII. CONCLUSION

This paper presents an alternative approach for solving and analyzing hydraulic pipe networks with Matlab/Simscape environment. The academic case study consists of finding the required flowrate of two sources while the topography of the hydraulic pipes network is known. The approach is compared to the one of the well-known Hardy Cross. The proposed approach shows good results with a simulation time less than 5 seconds. However, the algebraic sum of the head loss in each loop is less accurate than the one obtained in Hardy Cross method. The proposed approach offers more analysis possibilities than the one of the HCM. For example, the implementation of the flow sources solution makes it possible to find the desired flow at demand node. Future works will focus on the leaks analysis.

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