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Review

Novel method for looped pipeline network resolution

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ABSTRACT

It is proposed a novel method to solve looped pipeline network problems that seeks to deal with limitations of the available methods The problem is modeled as a nonlinear system of equations formed by equations that cannot be solved sequentially, characterizing the resolution as a simultaneous-modular procedure. The equations of the system are the differences between the final pressure of the pipes that end at the same network nodes and the difference between the specified and calculated design variables. At the solution both Kirchhoff's laws are met, being the method main advantages the no need of independent loops selection and the formulation of a reduced system of equation. Case studs with a small and a big looped water pipeline network, and an industrial installation with looped pipeline configuration, are solved. The latter shows the method applicability for design process, highlighting its advantages in comparison with the traditional simulation procedures.

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1. Introduction

The pipeline network problem is formulated when the flowrate and pressure in all pipes and nodes of a network are needed. The problem formulation requires the physical characteristics of the pipes and the specification of some network pressure and flowrate variables. Many networks problems are easily solved by a sequential procedure. However, when different pipes flow to a same node, or the network presents loops, different procedures must be employed.

In order to solve the looped pipeline network problem, it is very common the employment of the two Kirchhoff's laws. The first and the second laws, originally developed to solve electrical circuits problems, are equivalent, respectively, to the continuity and the energy conservation equation (Martinez and Puigjaner, 1988), and can be written as follow:

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1ª: The algebraic sum of currents at a node on a network of conductors is zero.

2ª: The directed sum of the electrical potential differences (voltage) around any closed circuit is zero.

Appling the laws on the looped pipeline network problem, the current at the first law is understood as the mass flow and the electrical potential at the second law is understood as the pressure drop. When solving the looped pipeline network problem employing the Kirchhoff's laws, one of the laws is satisfied in the problem modeling and the other one is satisfied solving a nonlinear system of equations (Cross, 1936). Based on the linearization of such system of equations, Cross (1936) proposed the most relevant methods to solve the problem, which are essentially a relaxation method suitable to solve the problem by hand (Gay and Middleton, 1970). Depending on which law is firstly satisfied in the modeling, different methods are obtained, named: *Method of Balanced Flow*, which firstly satisfies the first Kirchhoff's law; and *Method of Balanced Pressure*, which firstly satisfies the second Kirchhoff's law (Cross, 1936).

In order to improve the problem resolution, methods based on the partitioning of the problem representative matrix were developed (Sargent, 1978; Shacham, 1984), but the application on large problems was still not satisfactory (Martinez and Puigjaner, 1988). Furthermore, other linearization methods were developed (Krope et al., 2011) and, more recently, the Newton-Raphson method was applied to solve the looped pipeline network problem for both Hardy-Cross methods (Altman and Boulos, 1995; Brkic, 2011). As any Newton-Raphson application, the characteristics of the equations and the initial guesses of the dependent variables define the problem convergence property.

Analyzing the Hard-Cross procedures, the *Method of Balanced Flow* is appropriate to solve problems with known pressures at any point of the network. Firstly, the network model must be built satisfying the second Kirchhoff's law, assuming pressures at all network nodes and calculating the flowrates in all pipes. As the pressure nodes and, consequently, the calculated flowrates in pipes are not the problem solution, corrections at the node pressure must be made until the mass balance, first Kirchhoff's law, be satisfied. In principle, for the problem resolution, it is needed the employment of a pressure drop equation with explicit flowrate variable. Aiming the improvement of the problem resolution, for any pressure drop equation, new procedures were proposed for the iterative correction of the nodes pressure (Rao, 1987) or by using non-deterministic optimization techniques, such as *Simulated Annealing* (Yeh and Lin, 2008; Tospornsampam et al., 2007).

The *Method of Balanced Pressure* is suitable to solve problems when the inlet and outlet flowrates of the looped network are known. By satisfying, in the network modeling, the mass balance in the nodes, the nonlinear system of equation is formed by the energy conservation equations of the selected network pipeline loops. The main drawback of this method lies on the selection of such representative loops (Gay and Middleton, 1970; Rao, 1987), since the number of the network loops is commonly greater than the number of necessary equations to solve the problem, and not every loops group forms a solvable problem. In order to overcome this drawback, Gay and Middleton (1970) proposed a procedure to perform the initial choice of the representative network loops and to compute the pressure drop with the Darcy-Weisbach equation, and Martinez and Puigjaner (1988) proposed a procedure to choose the loops in large networks. Currently, this choice can be done by graph procedures and it is already known that the representative network loops must be verified for the independency among each other (Jha, 2007).

Aiming the use of the *Method of Balanced Pressure* on problems with specified pressure at the inlet or outlet network nodes, a procedure to obtain pseudo-loops equations, as found in Streeter and Wylie (1984) and Sârbu and Valea (2011), was developed. With this procedure, the method can be applied on networks with either pressure or flowrate as specified variables and, because of that, nowadays, the method is widely employed to solve any looped network problem.

Another method, called hybrid method, has no need to firstly satisfy any Kirchhoff's law, which leads to a looped pipeline network problem characterized by both node mass balance and energy conservation equations (Hamam and Brameller 1971; Todini and Pilati, 1987; Osiadacz, 1987; EPANET, 2015). The method has as main drawback the need of simultaneous resolution of large set of equations, making even more difficult the problem convergence.

Despite the greater attention on water pipeline network distribution, the introduced methods are applied on looped pipeline network flowing any kind of fluid, being applicable on wide industrial and urban pipeline installations. In industrial plants, the looped pipeline arrangements are found on by-pass of equipment, utilities distribution systems and firefight systems, for instance; and in urban installations, on heat gas, fuel gas and water distribution networks. The calculation of looped pipeline network of gas distribution systems has gained some attention given the higher difficulty on compute pressure drop (Krope et al., 2011; Woldeyohannes and Majid, 2011). Furthermore, the calculations of pumps, valves and pipe accidents pressure drops were incorporated into the looped pipeline problem, making possible the resolution of more realistic problems (Krope and Goricanec, 1991).

Currently, different methodologies can be employed to solve looped pipeline network problems. The identification and analysis of the pipes, devices and equipment's characteristics, the problem specifications and the flowing fluid must be done previously to make possible the choice of the best resolution method (Brkic, 2011).

In this work, a novel method for looped pipeline network resolution is proposed. The new method consists in attending the mass balance in the nodes (first Kirchhoff's law), group all equations that can be solved sequentially, identifying the ones that need simultaneous convergence. Such equations formulate the nonlinear system of equations of the problem being characterized by the differences between the final pressures of the pipes that ends on the same node, which replace the loop equations (second Kirchhoff's law), and the differences between specified and calculated design variables, which replace the pseudo-loop equations. With the proposed method, there is no need of identifying and selecting the independent loop equations, being more suitable to incorporate in a process simulator.

This paper is structured as follows: in Section 2, the proposed method is presented, highlighting the steps of modeling and the numerical resolution of the whole network problem. In Section 3, the developed methodology is demonstrated by the resolution of three looped pipeline network problems. The first and the second problems are a small and a big looped water pipeline network, respectively, with both of them introduced by Yeh and Lin (2008). The third one shows the method applied to an industrial looped pipeline, where pumps and pipe accidents compose the problem, showing that the method can be used in any process simulation problem. The conclusions of the work are presented in Section 4.

2. Proposed method

It is understood that the Hardy-Cross *Method of Balanced Pressure* is the most suitable procedure to solve the looped pipeline network problems, since it requires the simplest network modeling. The method allows the natural attendance of the mass balance in any network node, pipe or equipment; and the employment of pressure drop equations with explicit pressure drop.