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# An enhanced network design of natural gas pipelines by controlling gas flow: considering supply reliability and operation efficiency

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**Abstract** Due to the rapid expansion in cities and urban as well as its infrastructure, the existing natural gas network is unable to cover the new sections due to the pressure drop. In the present study, a comparison study of gas flow characteristics is conducted with three different solutions to accommodate the overloading. The first solution is to supply the network with a new main gas line and a new regulator. The second solution is to increase the pressure in the existing gas lines and gas regulators. The last proposed solution is to connect the main supply regulators with the main flow pipe which is called the loop pipe. The pressure and velocity fields of the natural gas in the network will be investigated numerically using Syner-GEE software and practically for different loading conditions. Furthermore, the cost of the three possible solutions is investigated to measure the best solution among them. The study is conducted and applied to four cities in Egypt which are, Girga, Qena, Qous, and Qeft. The results showed that the three possible solutions satisfy the minimum required pressure in the rare points in the gas network. Despite of that they have other different features. Adding a new regulator is considered an expensive solution and required other precautions. Increasing the regulators' pressures increases the gas flow as well as the gas velocity which is considered unacceptable. However, the proposed third solution of looping pipe provides less pressure field but maintains safety and good operation criteria.

**Keywords:** Natural gas network; flow characteristics; numerical simulation; Syner-GEE software.

## 1 Introduction

Natural gas, which is one of the cleanest and most efficient existing mineral energy sources, is important for the optimization of energy structures in the 21st century [1]. Generally, gas sources are located far from the consumers. Pipelines have become the main method to transport natural gas. For example, North Sea natural gas is transported from the continental shelf to processing terminals on the Norwegian mainland and fed into long export pipelines to continental Europe [2]. The natural gas networks are divided into three types; the high-pressure network which transports the gas from its source to the city then it dropped to the intermediate pressure via reduction stations. Then the gas flows through the intermediate pressure network which is considered the main pipe inside the city. The intermediate pressure gas is reduced through regulators to the low-pressure gas then it flown into low pressure networks to homes and domestic buildings[3]. The extension of the cities requires expansion to the existing gas network which leads to a drop in gas pressure as well as maloperation of the gas network[4].

There are many studies investigating the modeling of natural gas networks by numerical approach using different methods [5–8]. Furthermore, the likely extension of existing is also simulated numerically to show the flow characteristics variation [9-12]. Off-line simulation is typically applied for the analysis, decision support and optimization of pipeline networks [12,13]. Many efforts have been made the improvement of the numerical models [14–18] to get high simulation results of the gas flow field. Transient and steady flow modeling is conducted to simulate all flow features of this process [6].

Cost benefit analysis of the different solutions for natural gas networks is also investigated [19]. It was reported that the savings of the capital and operating costs are a big concern during the designing process of the natural gas network [20].

In this study, the flow characteristics of different pipeline networks will be investigated numerically using Syner-GEE software [21]. The pressure and velocity fields in each pipe connection are investigated for different four cities, Qena, Qous, Qeft, and Girga after adding the extension of new sections. The results of the flow pressure

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and flow velocity of the new network are compared with three different scenarios. The first scenario of adding a new regulator, the second scenario is to increase the pressure on the existing regulators, and the last proposed solution is to connect the main supply regulators with the main flow pipe which is called a loop pipe. The cost of the three solution scenarios is also compared with each other in order to evaluate the best design among them.

## 2. Problem Description

The aim of this study is to investigate the flow characteristics of four cities after adding a new section to the existing gas network. The gas pressure and gas velocity are investigated numerically using Syner GEE software for different three possible solutions for enhancing the network structure. The network structure before the extension is presented in Figure 1. It is clearly appearing from the figure that the network has five regulators that are used to reduce the intermediate pressure into low pressure gas that is supplied directly to the buildings. The network consists of a number of nodes and connections. The nodes' pressure must be between 50 to 100 mbar and the velocity in the connections must be less than 20 m/s to satisfy the safety operation.

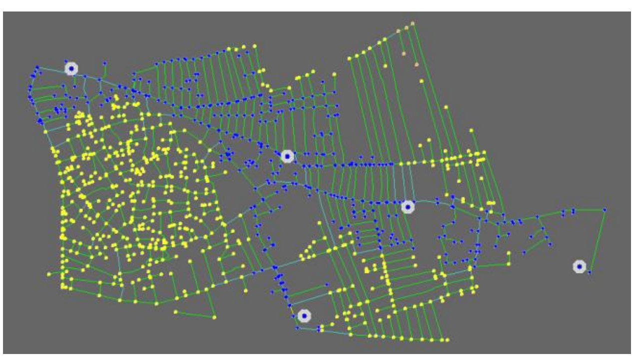


Figure 1. Network of Girga City before the extension.

After city extension, a new network section is added to the old network as shown in Figure 2. It is clearly appearing from the figure that the pressure of many nodes has a red color which indicates that the pressure is below 50 mbar. There are three solution scenarios are proposed to increase the gas pressure while maintaining the flow velocity at the acceptable limits. The first scenario is to increase the pressure of the regulators near the failed region. The second scenario is to add a new regulator in the failed region and the third scenario is to conduct a loop between the two adjacent regulators to the failed region.

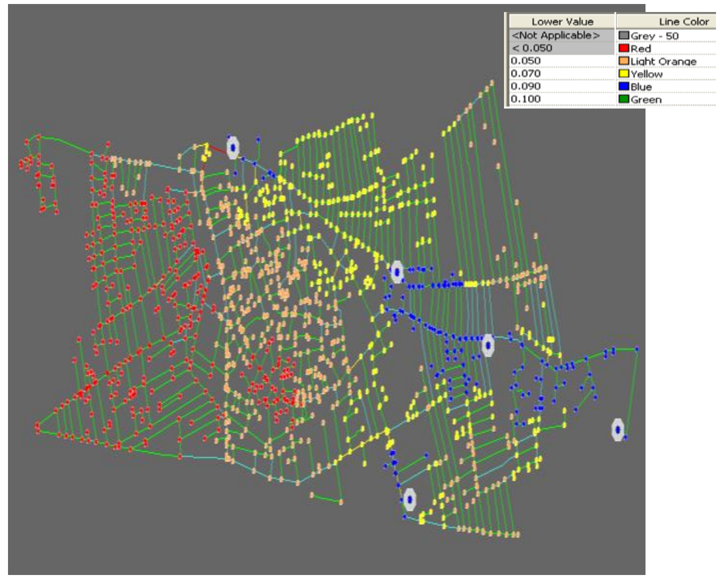



Figure 2 Network of Girga City after the extension.

## 3. Numerical Solution

The model of the piping system is constructed from non-linear mathematical equations based on the provided network information. Syner GEE numerical software is used to discretize and solve the non-linear equations. These equations represent network interconnection based on Kirchhoff's first law, which states that the flow into or out of a node in a network must sum to zero in order for mass to be conserved. The equation solutions provide predictions of pressures, flows, valve positions, pipe diameters, compressor powers and speeds. Adherence to Kirchhoff's law allows the development of a set of non-linear node continuity equations that are then solved with an iterative Newton-Raphson solution technique. This solution technique simultaneously solves the system of independent equations. For the independence of the system of equations, the hydraulic network model must have at least one unknown node flow and at least one fixed pressure. The application solves all equations in terms of nodal pressure, and then computes the resultant facility flows, given that facility flows are expressed as functions of unique constants and upstream and downstream pressures. The iterative process ideally results in a solution where all unknown facilities, unknown pressures, and unknown flows are solved within the set tolerances.

### 3.1 Mathematical model

The mathematical relationship of Kirchhoff's first law of a sample network as shown in figure 3 is expressed by the following equation:

$$F_j = \sum_{i=1}^{j} Q_i + QN_j \qquad j = 1 \dots NN \tag{1}$$

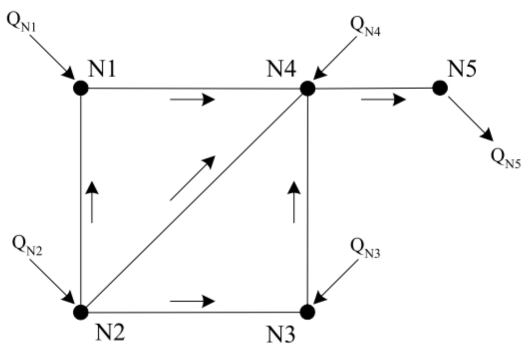



Figure 3 Sample network.

Consider a sample network of four nodes as shown in Figure 3. The set of linearly independent simultaneous equations resulting from the sample network system could be presented as shown in equation (2) [21]:

$$\begin{vmatrix} F_{N1} \\ F_{N2} \\ F_{N3} \\ F_{N4} \\ F_{N5} \end{vmatrix} = \begin{vmatrix} -Q_{N1,N4}+Q_{N2,N1} & 0 & 0 & 0 & 0 & +Q_{N1} \\ 0 & -Q_{N2,N1}-Q_{N3,N2} & 0 & -Q_{N4,N2} & 0 & +Q_{N2} \\ 0 & 0 & +Q_{N3,N2}-Q_{N4,N3} & 0 & 0 & +Q_{N3} \\ -Q_{N1,N4} & 0 & 0 & +Q_{N4,N3}+Q_{N4,N2} & -Q_{N5,N4} & +Q_{N4} \\ 0 & 0 & 0 & 0 & 0 & +Q_{N5,N4}-Q_{N5} \end{vmatrix} \tag{2}$$

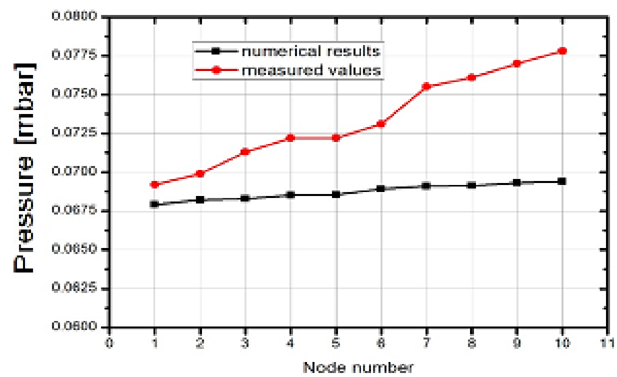
The Syner GEE numerical software is used to solve the system of the above simultaneous equations to find out the flow rates as well as the gas velocity at any point. Moreover, the Syner-GEE software employed the Darcy-Weisbach equation to calculate the pressure drop/friction coefficient in the pipe network.

### 3.2 Model Validation

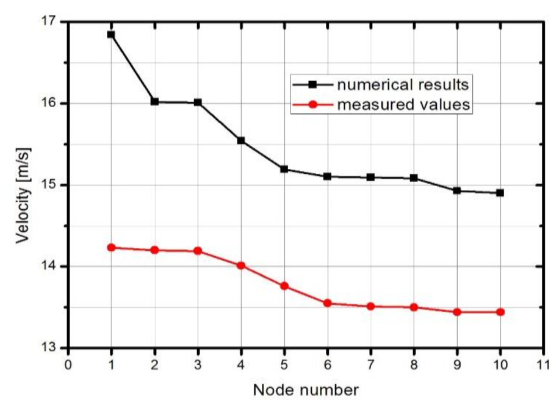
In order to validate the Syner GEE solution, the gas pressure of multiple nodes is measured practically then the values are compared with the Syner GEE simulation results. The measurements are taken during the rush hours with a time interval of 10 minutes to investigate the maximum flow demand. The nodes are selected based on their location to the supply pressure regulator where they spread on the whole network, nodes of minimum gas pressures. Moreover, the flow mean velocity is estimated experimentally by measuring first the mass flow rate of the gas in the pipe then it is calculated based on the following equation [22]:

$$V = \frac{\dot{m}}{A} = \frac{\dot{m}}{\frac{\pi}{4} d^2} \tag{3}$$

Figure 4 represents the validation between the measured values of the pressure and pressure and the predicted data using Syner GEE. The measured pressure is higher than the modeled pressure because the software is considering all demand nodes are opened however practically some of them may is not opened. On the other hand, the velocity of the simulation is higher than the measured values due to some of the demand nodes are not working at the measuring time. The variation between the measured and simulated values is not significant for both pressure and velocity.




(a) Pressure validation




(b) Velocity validation

Figure 4 Model validation with measured vales. (a) pressure validation and (b) velocity validation.

## 4. Results and Discussion

### 4.1 Flow characteristics

Girga city network of natural gas before and after the expansion were presented in Figures 1 & 2. All pressures and velocities were within the acceptable limits before the expansion however, they exceed the limits after adding the extension. It clearly appears from the figure that most of the new pipelines have a pressure below the acceptable limit with minimum pressure dropped to 0.025 bar at many nodes. The velocity field in the pipelines is about 22.35 m/s which is considered unsafe for corrosion and leakage.

#### 4.1.1 Increasing regulator pressure

The first scenario is to increase the pressure of the nearest regulator (number 5) to the expanded pipelines to increase the pressure at the failed nodes. Figure 5 represents the pressure field at increasing the regulator pressure to 0.135 mbar. Many trials are done to reach the minimum increase in the regulator pressure (0.135 mbar) and maintain the minimum pressure at all nodes at the acceptable range (between 0.05 to 0.1 bar). Figure 6 represents the pressure field at the extended area pipelines after increasing the regulator pressure to 0.135 bar. The minimum pressure is about 0.051 bar which is within the acceptable limit however the velocity in the pipes is changed due to increasing the regulator pressure. Figure 7 represents the pipes that have maximum velocity in the network after increasing the regulator pressure. It is appeared from the figure that the pipes near the regulator have a maximum velocity which is about 24 m/s, which is considered highly risky for the safety precautions.

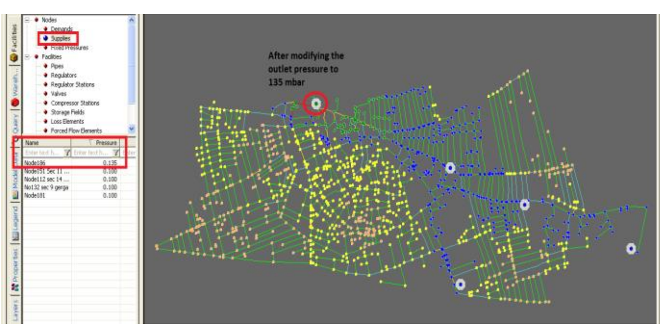



Figure 5 Natural gas network of Girga city after increasing regulator pressure.

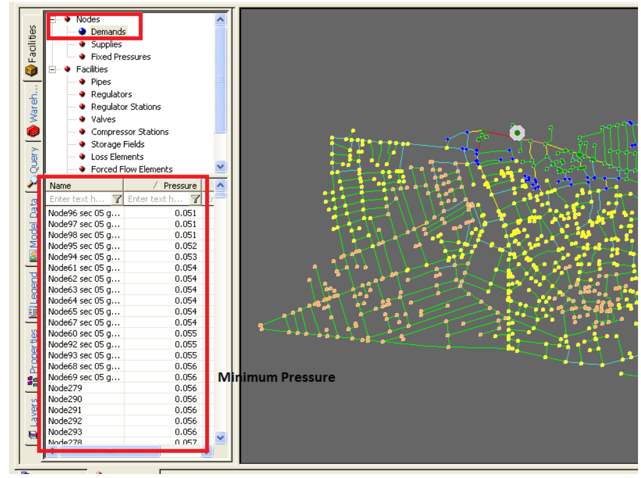



Figure 6 Natural gas network of Girga city after increasing regulator pressure, pressure field.

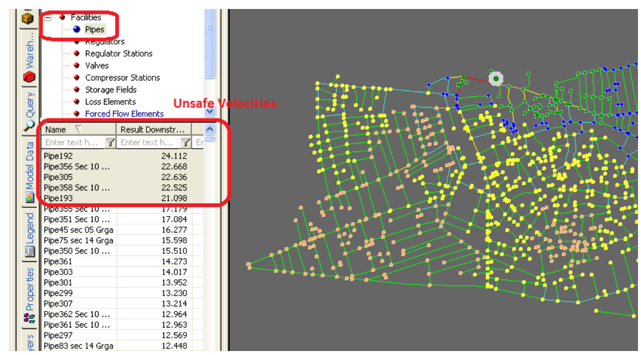



Figure 7 Natural gas network of Girga city after increasing regulator pressure, velocity field.

#### 4.1.2 Install a new pressure regulator

The most common scenario for resolving the expansion of the gas networks is to add new regulators to the newly expanded sector. This scenario is applied to Girga city expanded network to maintain the pressure and velocity at acceptable limits among the whole network pipes. Figure 8 represents the pipe network after adding a new regulator inside the new section. The location of the regulator is set after many trials to adjust the pressure and the velocity within the acceptable limits. The regulator pressures are all at 0.1 bar as recommended as shown in figure 8. The pressure field and the velocity field of the whole network are investigated after adding the new regulator. Figure 9 represents the minimum pressures and the maximum velocities at the networks in this scenario. It is founded that the minimum pressure on the network is 0.067 mbar and the maximum velocity is 15 m/s which are within the safety limits.

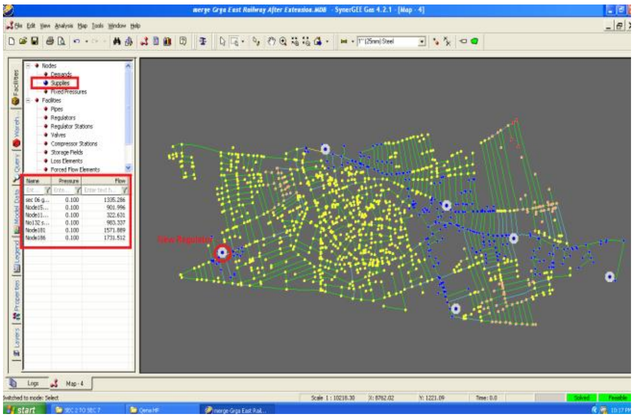
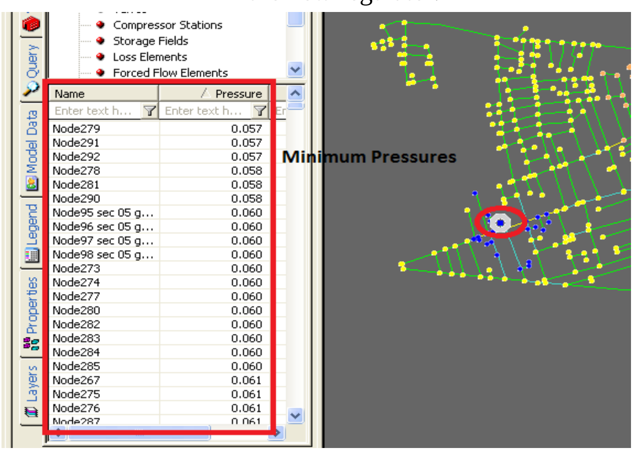
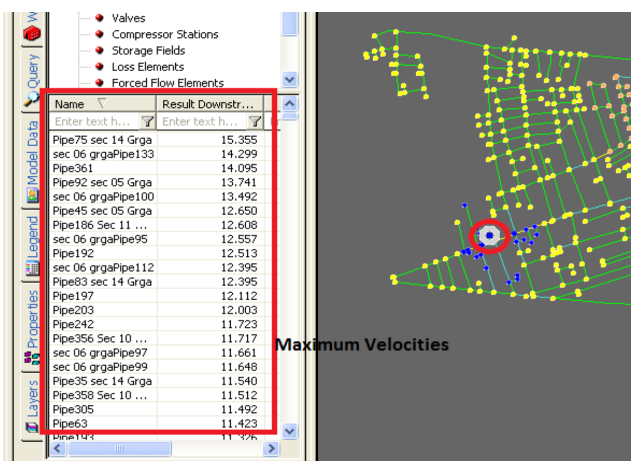


Figure 8 Natural gas network of Girga city after adding the new regulator.




(a) Pressure values




(b) Velocity values

Figure 9 Girga Natural gas network after adding the new regulator (a) pressure fields and (b) velocity fields.

### 4.1.3 Looping pipeline

Adding a new regulator to the new sector on the existing network is considered an expensive solution to overcome the expansion problem. The present scenario presents a less cost and more effective solution to the likely expansion of the existing pipe network. Looping is a technique in which we can enhance the network performance by controlling the pipe diameter and pipe connection. Figure 10 represents a solution to the expansion by controlling a pipeline diameter to be 250 mm than 125 mm to reduce the pressure loss in the pipes and decrease the velocity corresponding to the gas flow rate increase. The principle of this method goes through connecting the nearest two pressure regulators to the new sector with each other by a large diameter pipe. This large diameter pipe will equalize the pressure by about 0.1 bar along its field and could provide higher gas flow with relatively low velocity. As shown in the figure that the pressure and velocity fields are in the range of the acceptable limits. Moreover, the results indicate the values of the minimum pressure are about 0.053 bar and the maximum velocity in the network 16.7 m/s as indicated in Figure 11 below.

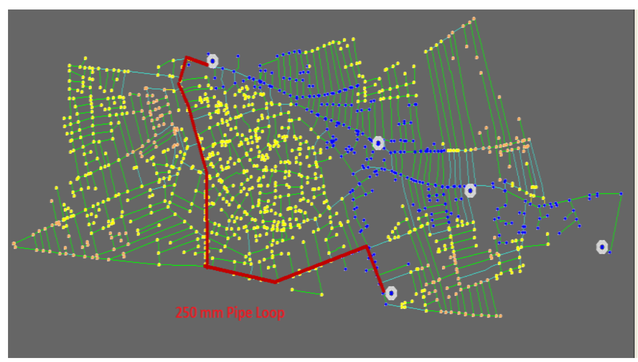
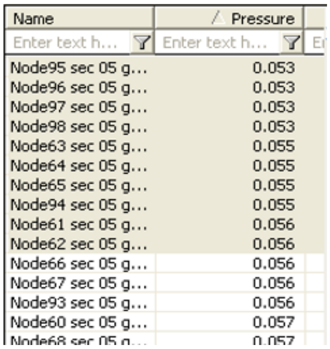
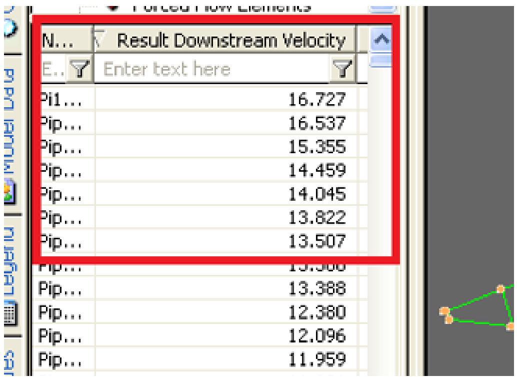



Figure 10 Natural gas flow characteristics of Girga network after conducting looping pipelines.



| Name | Pressure |
|---|---|
| Enter text h... | Enter text h... |
| Node95 sec 05 g... | 0.053 |
| Node96 sec 05 g... | 0.053 |
| Node97 sec 05 g... | 0.053 |
| Node98 sec 05 g... | 0.053 |
| Node63 sec 05 g... | 0.055 |
| Node64 sec 05 g... | 0.055 |
| Node65 sec 05 g... | 0.055 |
| Node94 sec 05 g... | 0.055 |
| Node61 sec 05 g... | 0.056 |
| Node62 sec 05 g... | 0.056 |
| Node66 sec 05 g... | 0.056 |
| Node67 sec 05 g... | 0.056 |
| Node93 sec 05 g... | 0.056 |
| Node60 sec 05 g... | 0.057 |
| Node68 sec 05 g... | 0.057 |

(a) Pressure values



| N... | Result Downstream Velocity |
|---|---|
| E... | Enter text here |
| Pi1... | 16.727 |
| Pip... | 16.537 |
| Pip... | 15.355 |
| Pip... | 14.459 |
| Pip... | 14.045 |
| Pip... | 13.822 |
| Pip... | 13.507 |
| Pip... | 13.388 |
| Pip... | 12.380 |
| Pip... | 12.096 |
| Pip... | 11.959 |

(b) Velocity values

Figure 11 Pressure and velocity fields of Girga Natural gas network after conducting looping pipeline.

It is appeared from the figure; the acceptable pressure level is 0.05 bar which is represented by the horizontal green dashed line. The pressure of the critical points before applying and solution scenarios have lower values than the acceptable level. On the other hand, the three different scenarios, increasing regulator pressure, adding the new regulator, or conducting a loop pipe, all provide the network with the sufficient pressures.

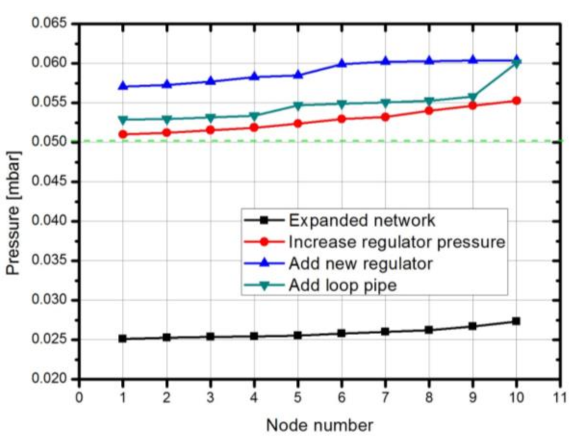



Figure 12 Minimum pressure at the critical points on Girga Natural gas network four different solutions.

Figure 13 represents the pressure at the most critical ten points in Qena city at different scenarios of solutions and compares them with the pressures after extensions. It is clearly appeared that the three solution scenarios produce a high gas pressure than the acceptable limit however adding a new regulator gives the higher-pressure values. The increasing regulator pressure scenario gives acceptable pressures but slightly greater than the acceptable limits. Moreover, adding the new regulator and conduct loop pipe provides stable pressure values to all critical points. This stability is satisfied when all critical points have approximate pressures which are satisfied for both scenarios while doesn't appear at increase regulator pressure scenario.

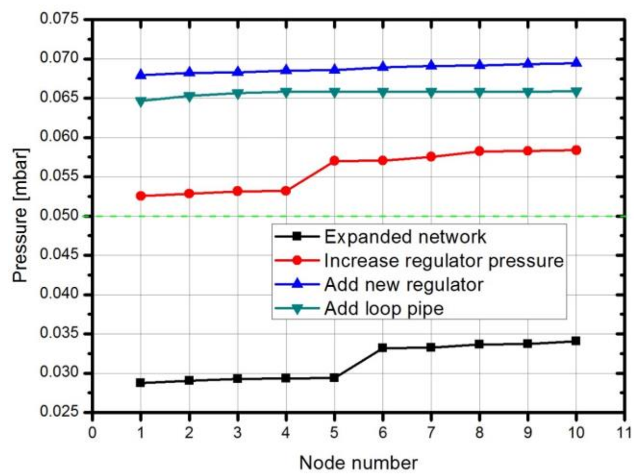



Figure 13 Minimum pressure at the critical points Qena Natural gas network four different solutions.

Figure 14 summarizes the pressure levels at the most critical demand points across the whole network for the three scenarios. As it is appeared, increasing the regulator pressure fails to raise the pressure to the green line, the acceptable pressure. This is likely occurred due to the great expansion in the network and the complexity of the network which dropped the pressure significantly. Add loop pipe to provide an acceptable pressure however add a new regulator to supply these critical points with high sufficient pressures as shown in the figure.

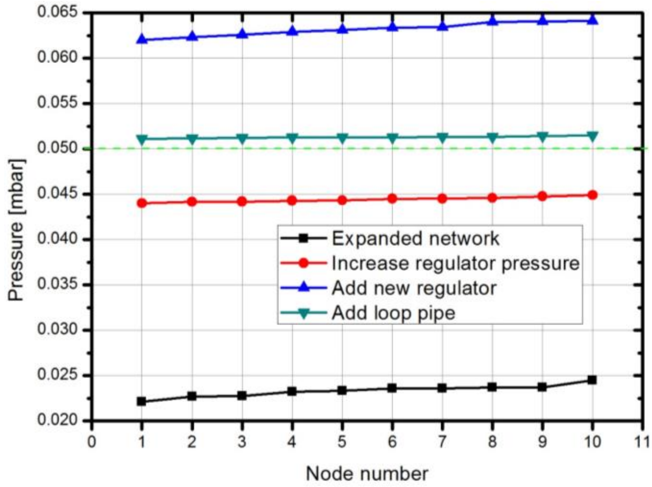



Figure 14 Minimum pressure at the critical points on Qeft Natural gas network four different solutions.

Figure 15 summarizes the pressure levels at the most critical demand points across the whole network for the three scenarios. As it is appeared, increasing the regulator pressure failed to raise the pressure to the green line, the acceptable pressure. This is likely occurred due to the great expansion in the network and the complexity of the network which dropped the pressure significantly. Add loop pipe to provide an acceptable pressure however add a new regulator to supply these critical points with high sufficient pressures as shown in the figure.

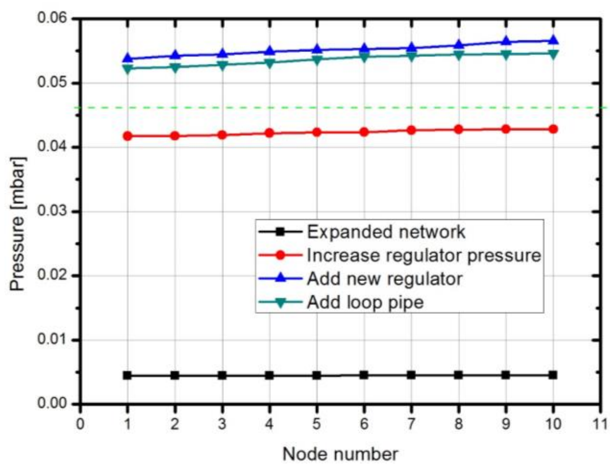



Figure 15 Minimum pressure at the critical points on Qous Natural gas network four different solutions.

### 4.2 Cost and benefit analysis

As it is discussed previously, both scenarios of installing the new regulator or installing the looping pipe are good solutions for the unplanned expansion of the natural gas network however, there are some other considerations must be taken during the evaluation process. These considerations are:

1. Installation and operation cost
2. Maintenance requirements.
3. Component cost.
4. Safety insurance.
5. Other limits and considerations.

#### 4.2.1 Installation and operation

The installation process of the pressure regulator includes preparing a concrete base to carry it and cover it for protection. On the other hand, the loop pipe needs excavation which is already performed for the main pipelines. The regulator must be frequently supervised by technicians to avoid gas pressure drops however the loop pipe doesn’t require any supervision [24].

#### 4.2.2 Maintenance requirements

Regulators consist of many components such as the diaphragm which maybe need to be replaced after its life time or in case of troubleshooting however pipes may be replaced under leakage conditions [25].

#### 4.2.3 Component cost

The pressure regulator costs approximately 250,000 L.E, however, the meter length of the pipe costs from 300 to 700 L.E based on pipe diameter.

#### 4.2.4 Safety Insurance

Pipes are submerged underground which is considered highly safe however, the regulator has a relief valve to release high pressure gas which is considered unsafe.

#### 4.2.5 Other limits and considerations

Regulators must be installed away from the buildings as a safety precaution to avoid fires and also they must be installed away from roads to avoid accidents.

From the flow characteristics study, the solution scenario of increasing regulator pressure failed to satisfy the safety and operating criteria. The cost analysis is conducted for the other two solution scenarios, adding a new regulator or installing a loop pipe. Table 1 summarizes the results of the cost analysis for both solutions. The table indicates that the loop pipe solution is generally better than adding the new regulator in general.

Table 1 comparison between two possible solution scenarios.

| No. | Criteria | Install pressure regulator | Install loop pipe |
|---|---|---|---|
| 1 | Acceptable operating pressure | Satisfied | Satisfied |
| 2 | Acceptable gas velocity | Satisfied | Satisfied |
| 3 | Primary cost | High | Low |
| 4 | Operating cost | Need | No need |
| 5 | maintenance | Need | No need |
| 6 | Safety insurance | High risk | Low risk |
| 7 | Other limits and consideration | Place consideration | None |

## 5. Conclusions

A new solution for enhancing the gas flow characteristics of the expanded gas network is proposed in this study. Installing loop pipe that connects regulators with each other is the proposed solution and its flow characteristics and installation cost are compared with two other solutions. The two other solutions are to increase the regulator pressure or add new regulators. The results indicate that adding a new regulator solution or installing a loop pipe satisfies the pressure and velocity requirements however increase regulator pressure solution produces high gas velocity in the network pipes. Installing the loop pipe has lower cost achievements compared with adding the new regulator.

## Nomenclature

| | | | |
|---|---|---|---|
| A | Area [m$^2$] | N | Node number |
| D | Diameter [m] | P | Pressure [Pa] |
| i, j | notations | Q | Flow rate [m$^3$/s] |
| $\dot{m}$ | Mass flow rate [kg/s] | V | Velocity [m/s] |

**Authors' Contributions**

Mohamed S. Hussin (Conceptualization: Lead; Data curation: Lead; Formal analysis: Lead; Funding acquisition: Lead; Investigation: Lead; Methodology: Lead; Project administration: Lead; Resources: Lead; Software: Lead; Supervision: Lead; Visualization: Lead; Writing – original draft: Lead; Writing – review & editing: Lead).
Ahmed N. Shmroukh (Data curation: Equal; Formal analysis: Equal; Investigation: Equal; Methodology: Supporting; Resources: Equal; Supervision: Supporting; Writing – review & editing: Supporting).
G.T.Abdel-Jaber (Formal analysis: Equal; Resources: Supporting; Software: Equal; Supervision: Supporting; Writing – review & editing: Equal).
Essam Hares (Formal analysis: Equal; Investigation: Equal; Methodology: Supporting; Supervision: Supporting; Resources: Supporting; Writing – original draft: Supporting; Writing – review & editing: Equal).

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