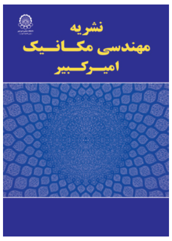

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Numerical Simulation of Transient Compressible Flow in Natural Gas long Transmission Pipelines Using a Suitable Parallel Algorithm

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ABSTRACT: Analysis of natural gas transient flow in transmission pipelines is one of the most important issues in the gas industry. Despite the previous studies, the accuracy and the computational time have yet considered as two important challenges in this field. In this paper, a parallel algorithm for numerical simulation of isothermal and non-isothermal gas flows is presented. Numerical analysis of the flow is performed using the implicit Steger-Warming flux vector splitting method. For parallelization, the computer program has been parallelized using Message Passing Interface library. In order to demonstrate the capabilities of the developed computer program, the flow inside two pipelines with different conditions is solved, and the results are validated. Then, some factors such as the computational time, reduction of the time, and the speed up criteria are obtained to demonstrate the computational efficiency of the proposed method. The results show that parallel processing method can significantly reduce computational time of natural gas flow in long transmission pipelines. Moreover, it is shown that application of this approach on the fine computational grids is more efficient than on the coarse grids.

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1- Introduction

Transmitting natural gas through the pipeline is yet the most important way for gas transmission. In this way, the governing equations of the transient natural gas flow must be numerically solved. On the other hand, natural gas transmission pipelines are often too long, and particularly when the flow simulation takes a long time, it is very time-consuming and expensive to predict the transient flow behavior. By parallel processing of the calculations, the problems can be implemented more quickly by using the existing equipment and technologies. As a result, the design process can also be completed in a shorter time and with a reduction in the costs.

In 1943, Lapple [1] first developed a solution for analyzing the gas flow in the horizontal pipeline and concluded that, in the short pipes, the assumption of the adiabatic flow is more logical than the assumption of the isothermal flow. In 2008, using nonlinear implicit finite difference method, Abbaspour and Chapman [2] solved the equations of continuity, momentum, and energy. In 1998, using SPMD programming model, Lepper [3] developed a three-dimensional simulation of the turbulence flow in the utility boilers and thus achieved a speed-up of 12 using 24 processors.

In this study, non-isothermal and isothermal flows of the natural gas inside pipeline have been taken into account. Then, the parallel processing has been introduced as a method for decreasing the time and increasing the speed of the calculations. Two pipelines have been studied as the samples.

2- Methodology

2- 1- Governing Equations

Modeling of the transient gas flow in the pipeline is performed based on the three equations of continuity, momentum, and energy together with an appropriate state equation. The first three equations are shown as the following system of equations:

$$\frac{\partial Q}{\partial t}+\frac{\partial E(Q)}{\partial x}-H(Q)=0 \quad (1)$$

The existing variables in Eq. (1) are vectors as follows:

$$Q=\begin{bmatrix}\rho\\ \rho u\\ e_0\end{bmatrix},\qquad E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ (p+e_0)u\end{bmatrix},$$
$$H(Q)=-\begin{bmatrix}0\\ \rho G\\ -\rho(q+uG)\end{bmatrix} \quad (2)$$

The fourth required equation for solving the gas flow in the pipeline is the state equation or the gas law:

$$p=\rho ZRT \quad (3)$$

For non-isothermal flow, all four equations are solved. However, in the particular case of isothermal flow, it is not necessary to solve the energy equation, and the remaining equations are the equations of continuity, momentum, and state.

In this work, to solve the governing equations, the implicit Steger-Warming flux vector splitting method has been

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employed. Using this technique, the finite difference form of the governing equations is as follows [4]:

$$-\left(\frac{\Delta t}{\Delta x}A^{+}_{i-1}\right)\Delta Q_{i-1}+\left[I+\frac{\Delta t}{\Delta x}\left(A^{+}_{i}-A^{-}_{i}\right)-\Delta t B_{i}\right]\Delta Q_{i}+\left(\frac{\Delta t}{\Delta x}A^{-}_{i+1}\right)\Delta Q_{i+1}=-\frac{\Delta t}{\Delta x}\left(E^{+}_{i}-E^{+}_{i-1}+E^{-}_{i+1}-E^{-}_{i}\right)+\Delta t H_{i} \qquad (4)$$

By solving this system for each time step, the flow variables in that step are calculated. In order to analyze the parallel solution of the flow, the pipeline is divided into several segments. For calculation of the gas pressure at the junction of the two segments, the assumption of the isothermal flow is taken into account. Using characteristic lines, discretized equations, and the conservation of mass at the junction, Eq. (5) for calculating the gas pressure at the junction of the two segments is obtained:

$$p_{JUNC,j}=\left(\frac{c}{2A_{r}}\right)\times\left[\left\{\begin{array}{c}W^{in}_{K-1,j-1}+\frac{A_{r}}{c}p^{in}_{K-1,j-1}-A_{r}\Delta t\\ \times\left[\frac{f^{in}}{2\left(A_{r}\right)^{2}Di}v^{in}_{K-1,j-1}W^{in}_{K-1,j-1}\left|W^{in}_{K-1,j-1}\right|\right]\end{array}\right\}-\left\{\begin{array}{c}W^{out}_{1,j-1}-\frac{A_{r}}{c}p^{out}_{1,j-1}-A_{r}\Delta t\\ \times\left[\frac{f^{out}}{2\left(A_{r}\right)^{2}Di}v^{out}_{1,j-1}W^{out}_{1,j-1}\left|W^{out}_{1,j-1}\right|\right]\end{array}\right\}\right] \qquad (5)$$

2- 2- Parallel Processing

Parallel processing is a method in which the larger problems are subdivided into some smaller problems that can easily be solved in the parallel state. Message Passing Interface (MPI) standard is one of the most common and powerful standards used in the parallel programming. In the present study, for dividing the problem, the geometric domain decomposition method has been considered. After solving the problem, for evaluation of the performance, the amount of the increase in the speed of calculations (i.e., the amount of decrease in the time of calculations) has been examined.

3- Results

3- 1- Test Case 1

The flow, in this case, is the isothermal flow inside a closed-end pipe, in which there is no fluid flow initially. At the start of the simulation time, the inlet pressure suddenly increased. Simulation time of the problem is 200 min. The changes of the flow rate and pressure are investigated. After parallelizing the program, the flow in the pipe is solved for both parallel and serial states, and the solution time for each state is obtained. Fig. 1 shows the speedup diagram for the several solution grids.

As indicated in Fig. 1, by further discretizing of each pipe segment (i.e. increasing the nodes in the computational grid)

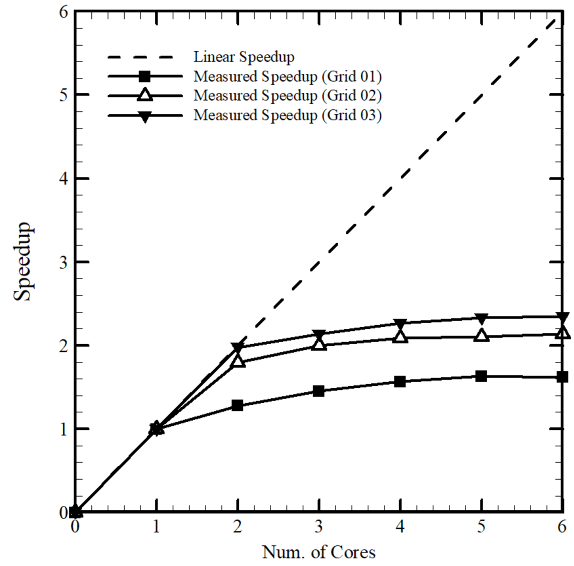

Figure 1. Speedup diagram for several solution grids

with the fixed number of cores, the efficiency of the algorithm gets closer to the ideal linear state. This adjustment can be due to the increase of the calculations with respect to the data exchange among the cores. Moreover, the efficiency of the algorithm moves away from the ideal state by increasing the number of the cores with the fixed number of the nodes. This result can be explained by the increased amount of data exchange among the cores.

3- 2- Test Case 2

The flow studied in this section is the non-isothermal and adiabatic flow inside a pipeline. The steady state flow results are employed as the initial conditions for a transient solution. The boundary conditions for the transient state are time-varying pressure and sudden increase in the inlet temperature, while the outlet pressure remains constant. The parallel processing program is performed for several computational

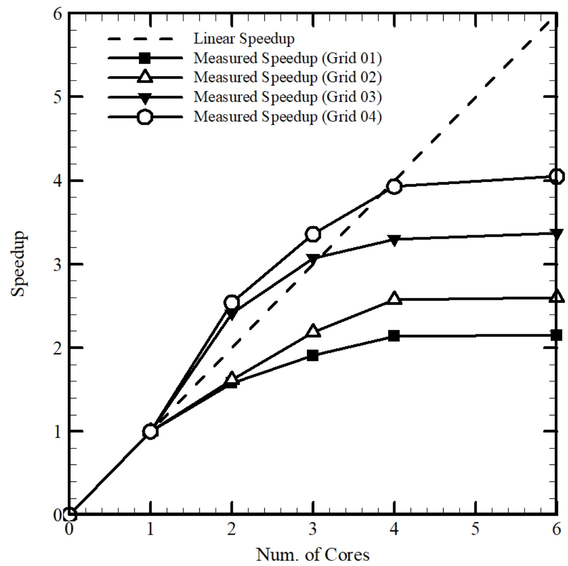

Figure 2. Speedup diagram for several solution grids

grids, while the computational time of these performances is compared, and the speedup and efficiency diagrams are provided. Similarly, in this pipeline, by increasing the number of the cores as well as by increasing the number of the nodes, the speedup increases.

4- Conclusions

In this study, simulation of the transient flow in the pipeline for isothermal and non-isothermal flows and the design of a parallel algorithm for solving the problem are taken into account. Verification of the obtained results shows the precision and accuracy of the suggested numerical method. In this work, the parallel processing technique and MPI method have been used to increase computational speed. Conformity of the responses in the parallel and serial states verifies the efficiency of the suggested parallel algorithm. Besides, the results of the implemented parallel processing program demonstrate a significant decrease in the time and a considerable increase in the speed of the solution.

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