

NOTES FOR IMPLEMENTATION OF VITALY-ANATOLY'S SCHEME ON A NETWORK

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1. INTRODUCTION

For a single pipe, the scheme is easy to understand and implement when given the initial conditions and the boundary conditions. However, complications arise when we apply it for a network of pipes and compressors.

To start with, for each pipe, assume a base grid of pressure/density (p/ρ) that matches the end-points, so that the grid for flux ϕ is staggered.

Given initial conditions for both variables (pressure/density at t_0 and flux at $t_0 + \Delta t/2$), it is possible to advance all the internal nodes for density to the next time instant ($t_0 + \Delta t$) by using the discretized equation of balance of mass. The pressure at the junctions however, cannot be calculated independently, and we need to satisfy the nodal balance to get the junction pressures for $t_0 + \Delta t$.

For this we shall use the flux at the end points, corresponding to the values at the ghost points, given by

$$(1) \quad s\phi_R^{n+1/2} = -\frac{s\Delta x}{\Delta t}\rho^{n+1} + \frac{s\Delta x}{\Delta t}\rho^n + s\phi_R^-$$

$$(2) \quad s\phi_L^{n+1/2} = \frac{s\Delta x}{\Delta t}\rho^{n+1} - \frac{s\Delta x}{\Delta t}\rho^n + s\phi_L^-$$

where ϕ_R^-, ϕ_L^- are the internal nodes for flux closest to the ghost points. We use the letters L, R to denote the left and right ends, where flow is assumed to be from left to right. Substituting these equations into a nodal balance for the fluxes converts them into equations for junction pressure which can then be solved for. Note that because of the staggered grid in space and time, we specify a steady-state balance of junction fluxes at time level $n + 1/2$ which in turn yields an equation that describes the nodal density at time level $n + 1$. If the formulation were implicit like Kiuchi's method, then density and flux would be collocated in both space and time so that one would have to make some approximation to derive an equation that can determine nodal density at level $n + 1$. Kiuchi defines a "junction volume" and replaces the fluxes with some kind of pressure relation from a pipe flow approximation to obtain a nonlinear equation for junction pressure at $n + 1$ when starting from the mass conservation PDE. Another possibility could be simple time-lagging of fluxes along with choice of "junction volume" to have a simple ODE for junction pressure that can be solved with a backward Euler approximation.

2. JUNCTION WITHOUT COMPRESSORS

At a node, say i_0 , suppose there are incoming pipes i_1, i_2, i_3, \dots , outgoing pipes o_1, o_2, o_3, \dots , and supply $q_{i_0}(t)$. We assume that for pipe i , $\text{sgn}(i) = +1$ if incoming, and -1 if outgoing, and supply is positive, withdrawal is negative. The notation $u \in e(i_0)$ will be used to denote a pipe u that has node i_0 as one end.

Then, we can substitute pipe fluxes in terms of densities from above to get

$$(3) \quad \left[\sum_{u \in e(i_0)} \frac{s_u \Delta x_u}{\Delta t} \right] \rho^{n+1}(i_0) = q_{i_0}(t) + \left[\sum_{u \in e(i_0)} \frac{s_u \Delta x_u}{\Delta t} \right] \rho^n(i_0) + \sum_{u \in e(i_0)} \text{sgn}(u) s_u \phi_u^-(i_0)$$

where $\phi_u^-(i_0)$ indicates that we want the flux value ϕ^- at the end i_0 for the pipe u , and s_u stands for cross-sectional area of pipe u .

This equation can be solved for $\rho^{n+1}(i_0)$ since everything else is known.

Thus the algorithm may be understood as the sequence of steps:

- (1) Given ρ^n everywhere, and $\phi^{n+1/2}$ at all internal nodes in network (initial condition)

- (2) Calculate ρ^{n+1} for all internal nodes of all pipes
- (3) Find ρ^{n+1} on pipe boundary (graph nodes)
- (4) Now calculate $\phi^{n+1+1/2}$ for all *internal* nodes of all pipes
- (5) $\phi^{n+1/2}$ at pipe ends can only be calculated when ρ^n, ρ^{n+1} are known.

Note that if the node i_0 is a *slack node*, then the pressure $p(i_0)$ is always known and there is nothing to do.

3. JUNCTION WITH COMPRESSORS

For a compressor c between nodes i and j , it is assumed that the flow is unidirectional only. That is, *we do not deal with flows wherein $\alpha \geq 1$ in one flow direction and $\alpha = 1$ if flow is in the reverse direction.* Moreover, one of the following *must* be known/given:

- (a) mass flow through compressor $f_c(t)$
- (b) Compressor ratio $\alpha_c(t)$
- (c) Discharge pressure of compressor

3.1. Mass flow given. If at a node i_0 , we have a compressor with condition (a), we can treat the given mass flux $f_c(t)$ as a supply term and add $\text{sgn}(c)f_c(t)$ on the RHS. Once again, the sign is +1 for incoming compressor and -1 for outgoing. Same process is followed if we have multiple compressors at a node i_0 with condition (a).

3.2. Compressor ratios given. For reasons that will become clear subsequently, we assume that our network is such that if a compressor c has nodes i and j , at least one of i or j must be such that *c is the only compressor attached to that node, i.e., one of the nodes must be what we define subsequently as a Level 1 node.* Let us record the implication of this statement carefully. This statement *does not* rule out nodes where multiple compressors connect. Neither does it prohibit such nodes from being neighbours. It only prevents the connecting edge between two such nodes from being a compressor. Stated another way, if nodes i, j have multiple compressors, our assumption rules out a compressor connecting i, j , but a pipe may still connect i, j .

Given a network satisfying the restriction, let us start by considering all *slack* nodes first. At a slack node i_0 , if there is a compressor c with compressor ratio α_c , then the density at the node lying at other end of the compressor is given by multiplying factor α_c if compressor is outgoing at i_0 ($\text{sgn}(c) = -1$, but the factor is $1/\alpha_c$ when $\text{sgn}(c) = +1$, i.e., incoming at i_0).

Now for a non-slack node i_0 , we have multiple incoming/outgoing, incoming compressor ic and outgoing compressor oc whose ends are nodes I and O respectively. Let us suppose that at the other end of ic , which is node I , there is supply $q_I(t)$, and pipes $e(I)$ and similarly for compressor oc at node O . In subsequent sections, we will see that i_0 is a Level 2 node connected to Level 1 nodes I and O . The formula we derive can be easily simplified for the case when the node i_0 is a Level 1 node.

Then, we have $\rho^{n+1}(i_0) = N/D$ where

$$\begin{aligned}
N = & \sum_{u \in e(i_0)} \frac{s_u \Delta x_u}{\Delta t} \rho^n(i_0) + \sum_{u \in e(i_0)} \text{sgn}(u) s_u \phi_u^-(i_0) + q_{i_0}(t) \\
& \sum_{v \in e(I)} \frac{1}{\alpha_{ic}} \frac{s_v \Delta x_v}{\Delta t} \rho^n(i_0) + \sum_{v \in e(I)} \text{sgn}(v) s_v \phi_v^-(I) + q_I(t) \\
& \sum_{w \in e(O)} \alpha_{oc} \frac{s_w \Delta x_w}{\Delta t} \rho^n(i_0) + \sum_{w \in e(O)} \text{sgn}(w) s_w \phi_w^-(O) + q_O(t)
\end{aligned}$$

and

$$D = \sum_{u \in e(i_0)} \frac{s_u \Delta x_u}{\Delta t} + \sum_{v \in e(I)} \frac{1}{\alpha_{ic}} \frac{s_v \Delta x_v}{\Delta t} + \sum_{w \in e(O)} \alpha_{oc} \frac{s_w \Delta x_w}{\Delta t}$$

We can now see that the assumption we made about the network prevents the stencil for the given node from expanding further than the other end of the compressors.

3.3. Delivery pressure given. If at node i_0 , there are multiple pipes but a single compressor c (from node I) that delivers with given pressure $p(i_0)$, then one can write

$$(4) \quad \sum_{u \in e(i_0)} \text{sgn}(u) s_u \phi_u^{n+1/2}(i_0) + f_c(t) = q_{i_0}(t)$$

Now $\phi_u(i_0)$ may be computed in terms of $\rho^{n+1}(i_0), \rho^n(i_0), \phi_u^-(i_0)$ so that one solves for $f_c(t)$. Once known, the flux is used at node I on other end of c to find the pressure, and thus the value of α is determined.

Let us write out the final equation after eliminating $f_c(t)$.

$$\begin{aligned} D &= \sum_{v \in e(I)} \frac{s_v \Delta x_v}{\Delta t} \\ N &= \left[\sum_{v \in e(I)} \frac{s_v \Delta x_v}{\Delta t} \right] \rho^n(I) + \sum_{v \in e(I)} \text{sgn}(v) s_v \phi_v^-(I) + q_I(t) \\ &\quad + \left[\sum_{u \in e(i_0)} \frac{s_u \Delta x_u}{\Delta t} \right] [\rho^n(i_0) - \rho^{n+1}(i_0)] + \sum_{u \in e(i_0)} \text{sgn}(u) s_u \phi_u^-(i_0) + q_{i_0}(t) \\ \rho^{n+1}(I) &= N/D \end{aligned}$$

Note that if there are two compressors delivering to same node with a given delivery pressure, then it is not possible to solve for both mass flows from one equation. Even if we develop equations for the nodes at other end of the compressors, α being unknown means that we cannot eliminate any quantities and solve. This is a limitation of this formulation and hence *we shall not consider networks where, at a node more than one compressor delivers with specified pressure.*

3.4. Combination of above given. Let us introduce the terms Level 0, Level 1 and Level 2 vertices to formalize the network restrictions alluded to in the previous section. A Level 0 vertex has no attached compressors while at a Level 1 vertex, there is exactly one compressor attached. A Level 2 vertex can have 2 or more compressors attached.

The idea behind the classification is that to solve for pressure/density at a Level 0 vertex, information at that particular vertex alone is sufficient. At a Level 1 vertex, on the other hand, one needs information at that vertex as well as at the one vertex that is at the other end of the attached compressor. At a Level 2 vertex, one needs information at that vertex as well as every vertex at the other end of every attached compressor (since we have assumed they are all Level 1 nodes). Clearly, computation at a Level 2 vertex is tedious but manageable as it is restricted to immediate neighbours. However, the stencil would become intractable if Level 2 vertices were connected by compressors. Thus, we assume certain restrictions on the network topology as follows.

We shall assume that the network satisfies three conditions:

- (1) Two Level 2 vertices cannot be connected by a compressor, i.e., at a Level 2 vertex, the other end of every compressor must be Level 1. This condition can be stated alternatively as: there can be at most two compressor elements in series in the network.
- (2) A vertex cannot be the delivery end of two compressors with delivery pressure controls.
- (3) A compressor cannot deliver to a slack node.

These conditions are not very restrictive in reality and are simply pathological cases we want to avoid (See Figure 1). For networks that satisfy the above restrictions, we shall write down the equations for the pressure of a general Level 2 vertex (and its Level 1 neighbours) in two common configurations (Figure 2). Thus, if we cycle through all Level 2 vertices of the network and calculate the densities, then all Level 2 neighbour vertices can be updated automatically, ensuring all vertices do get updated.

The fourth condition depicted in Figure 1 has to do with postprocessing to compute the compressor flows and will be detailed in Section 3.5.

The density at vertex i in the configuration in Figure 2a is determined through

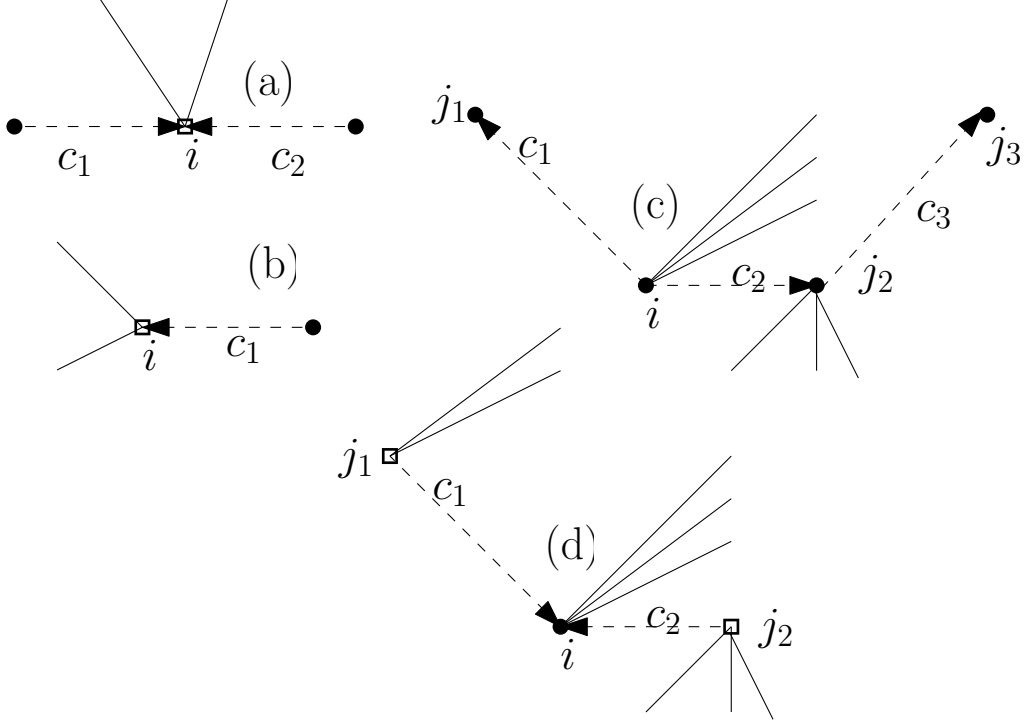


FIGURE 1. Illustration of the three topologies that are explicitly forbidden and a fourth configuration that is excluded purely for ease of postprocessing. (a) Two incoming compressors at i with discharge pressure control, (b) a slack node i with incoming compressor, (c) connected Level 2 nodes due to three compressors in series, and (d) Both compressors at a Level 2 vertex connected to slack (Level 1) vertices. This last configuration is purely to ease postprocessing of compressor flows.

$$\begin{aligned}
 & \left[\sum_{u \in e(i)} \frac{s_u \Delta x_u}{\Delta t} + \sum_{u \in e(j_2)} \alpha_{c_2} \frac{s_u \Delta x_u}{\Delta t} \right] (\rho^{n+1}(i) - \rho^n(i)) = \sum_{v \in e(j_4)} \left[\frac{s_v \Delta x_v}{\Delta t} \right] \cdot (\rho^n(j_4) - \rho^{n+1}(j_4)) \\
 (5) \quad & + \sum_{v \in e(j_5)} \left[\frac{s_v \Delta x_v}{\Delta t} \right] \cdot (\rho^n(j_5) - \rho^{n+1}(j_5)) + \sum_{v \in \{j_2, j_4, j_5, i\}} \left(q_v^{(n+1/2)}(t) + \sum_{u \in e(v)} \text{sgn}(u) s_u \phi_{u-}^{(n+1/2)}(v) \right) + f_{c_3}^{(n+1/2)}
 \end{aligned}$$

Since $\rho^{(n+1)}(j_4), \rho^{(n+1)}(j_5)$ are already known, once $\rho^{(n+1)}(i)$ is determined from (5), $\rho^{(n+1)}(j_2)$ is also found. In this configuration (Figure 2a), we *do not* solve for $\rho^{(n+1)}(j_3)$ but it will be determined separately when we land at vertex j_3 . The treatment of vertex j_3 is different because the compressor c_3 has mass-flow specified, and thus it is treated similar to the injection $q(i)$ at the vertex i . In practice, we will directly solve for $\rho^{(n+1)}(j_3)$ to ensure that all Level 1 neighbours of i are updated. This is necessary because our strategy is built around visiting Level 2 nodes first, and then doing Level 1 and Level 0 nodes.

In this scenario (see Figure 2b, the density at the base vertex i is already known, since we have now reversed the direction of compressor c_4 . However, we develop the equations for density at vertex j_4 as

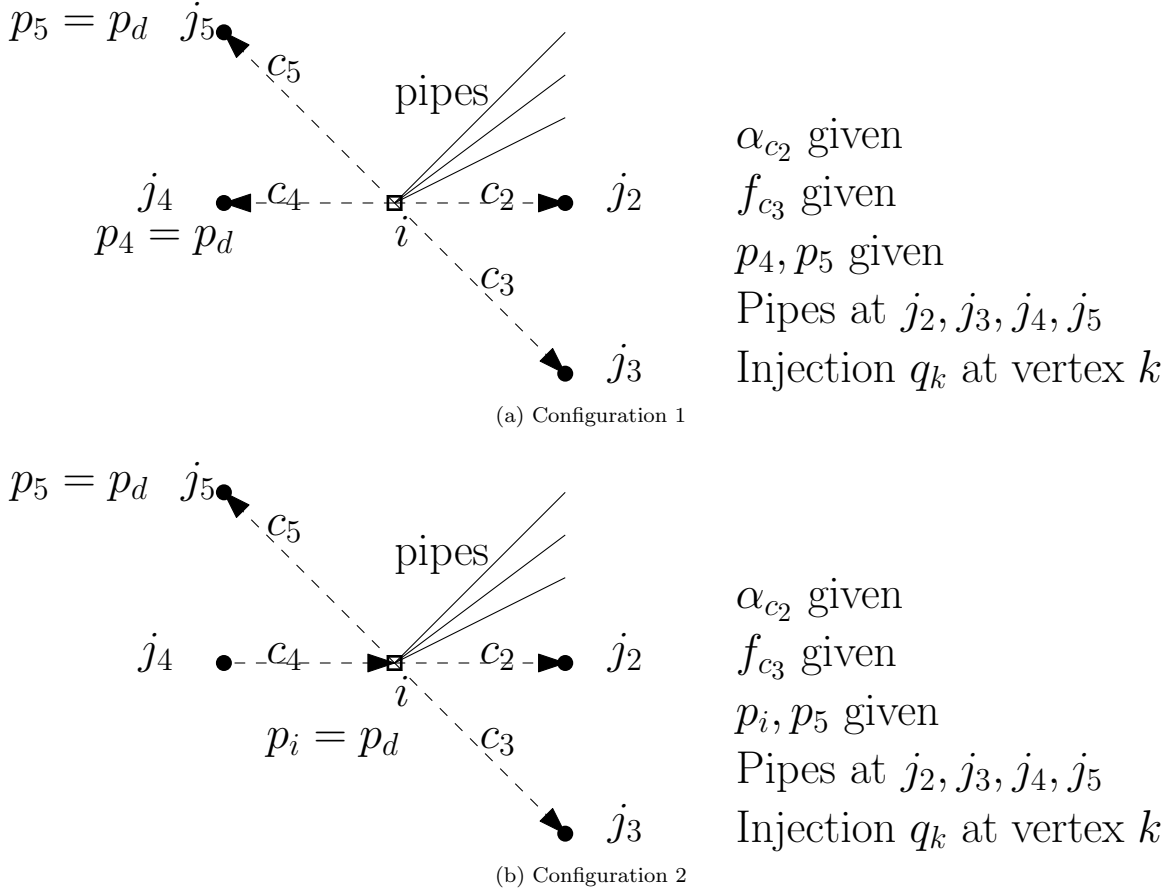


FIGURE 2. Considering vertex i , which is a Level 2 vertex, we determine vertex densities at i and its neighbours j_2, j_3, j_4, j_5 which are Level 1 vertices connected to i by compressors. The network restrictions stated earlier imply that for these configurations, c_4 and c_5 can be outgoing compressors, but they cannot both be incoming compressors, and p_5, p_4 in Figure 2a and p_5, p_i in Figure 2b cannot be slack nodes.

$$\begin{aligned}
& \left[\sum_{u \in e(j_4)} \frac{s_u \Delta x_u}{\Delta t} \right] (\rho^{n+1}(j_4) - \rho^n(j_4)) = \sum_{v \in e(j_5)} \left[\frac{s_v \Delta x_v}{\Delta t} \right] \cdot (\rho^n(j_5) - \rho^{n+1}(j_5)) \\
& + \left[\sum_{u \in e(i)} \frac{s_u \Delta x_u}{\Delta t} + \sum_{u \in e(j_2)} \alpha_{c_2} \frac{s_u \Delta x_u}{\Delta t} \right] (\rho^n(i) - \rho^{n+1}(i)) \\
(6) \quad & + \sum_{v \in \{j_2, j_4, j_5, i\}} \left(q_v^{(n+1/2)}(t) + \sum_{u \in e(v)} \text{sgn}(u) s_u \phi_{u-}^{(n+1/2)}(v) \right) + f_{c_3}^{(n+1/2)}
\end{aligned}$$

It can be seen that equations (5) and (6) are identical; we have simply transposed terms to reflect the known and unknown terms.

- The case of multiple incoming/outgoing compressors such as c_2 with given compressor ratios is easy to generalize. The compressor ratio will appear as $1/\alpha_c$ for incoming compressors in (5), (6).
- Similarly multiple compressors with given massflux are handled in the same way as c_3 , i.e., the densities are solved for after determining the density at the Level 1 “root” vertex i .

- Multiple outgoing compressors with discharge pressure control, such as c_4 , c_5 in Figure 2a are no problem.
- However, if c_4 be incoming, it must be the sole incoming compressor with discharge pressure control. Else the vertex equations cannot be solved locally (since it violates condition (2) above)

3.5. Postprocessing and calculation of compressor flows. If at least one end of a compressor C is a Level 1 *non-slack* vertex, then the flow through C at a time instant can be inferred from an application of the balance of mass at that end, since pipe flows and injection are known and the only unknown is the compressor flow. However, the flow cannot be determined if the compressor C connects a Level 1 *slack* node with a Level 2 node since now slack injection itself is unknown at the Level 1 node, and at the Level 2 node there are at least 2 unknown compressor flows. However, if in the first round of computation, all compressor flows at the Level 2 node except C become known, then one can again apply the balance of mass at the Level 2 node to infer the flow through C.

The only reason that another compressor flow (other than C) at the Level 2 node could remain unknown after the first round of computation is precisely the configuration (d) in Figure 1 wherein, another compressor is analogous to C and connected to a slack node. Hence, in order to ensure all compressor flows are determined, we rule out the configuration (d) in Figure 1.

3.6. Advantages of this formulation. In case of disruptive events, the network topology may change in the following ways:

- (1) A compressor may malfunction, leading to it blocking flow completely (in which case one can change its control to be a low value of mass flow)
- (2) Opening and closing of valves correspond to control values of mass flow changing from one value to another in a specified time interval
- (3) A compressor with given ratio may instead be operated to deliver at a given pressure or vice versa

This list is representative, and by no means exhaustive. However, the point to note is that, network changes of this kind are easy to handle, and it is reflected locally in the equations for the vertex associated with the component.

Note that the time marching step for internal nodes associated with mass flux and density are inherently parallel operations and may be performed as such. However, one can go further and check if it is possible to reduce the set of junctions to the smallest possible set such that each junction and its neighbours are disjoint from the rest thus ensuring that we can perform computations for each of these vertices in parallel too. In the absence of such a decomposition however, one must visit each junction serially, for parallel operations will result in a race condition.

4. DATA STRUCTURES AND SEQUENCE OF OPERATIONS FOR JUNCTION EQUATIONS

- (1) For a pipe between nodes i, j , there will be a grid for ρ, ϕ . Also, a field to access $\phi^-(i), \phi^-(j)$.
- (2) For each node, a flag to indicate if its pressure value has been updated in this current step.
- (3) For each node, a list of *all* pipes and compressors attached, a flag to indicate incoming/outgoing, and a compressor ratio (set to 1 if pipe). Note that this might include information about pipes at neighbouring nodes if compressors with unknown fluxes are present.
- (4) Then visit each Level 0/1 node, check if pressure value update flag is true; if so, exit and go to next node. Else perform computations at node, and update pressure at neighbouring nodes if relevant.
- (5) Once all nodes updated, reset pressure update flag to false
- (6) Now update fluxes
- (7) We can start with a steady-state solution of ϕ, ρ as initial conditions, where we will assume that the nodal injections of the steady-state problem are held constant for time interval $[0, \Delta t/2]$

5. GLOBAL FORMULATION

The way to solve this problem without any restrictions on network topology is to form the full matrix system and solve the system simultaneously.

- (1) Proceed as follows to first calculate the numbers of dofs in the problem, given that there are N nodes in total, of which N_s are slack nodes, and there are n_c compressors.

- (2) The number of nodal pressure dofs would be $N - N_s$.
- (3) For each compressor, we create either (i) 2 dofs, $f_c, 1/\alpha_c$ if delivery pressure is specified or (ii) single dof f_c if α_c is specified, or (iii) no dofs if $f_c(t)$ is given.
- (4) For each of the $N - N_s$ nodes i_0 , we write the balance equation that involves the nodal pressure $p(i_0)$, and compressor mass fluxes f_c if unknown.
- (5) For each compressor for which f_c is unknown, we write an equation. Either $(1/\alpha_c)p(i_0) - p(j) = 0$ if α_c is given. Else if delivery pressure p_d is given, then $(p_d)1/\alpha_c - p(j) = 0$.
- (6) The dofs thus comprise of $p_i, f_c, 1/\alpha_c$. If all compressors have mass flow given, only p_i to solve for. If all compressors have α_c given, then solve for p_i, f_c .
- (7) Will need to have a node to dof map and vice versa for use in every time step.
- (8) The system matrix will be sparse, but because $\alpha_c(t)$ and Δt may change with every time step, will need to evaluate in each step. RHS depends on previous time step solution, hence obviously needs updating each step. However, this algorithm does not take advantage of the local nature of junction computations, and will result in the computational overhead of repeated calculation and assembly of the global matrix if there are topology changes.

6. NON-DIMENSIONALIZATION

Let us choose the nominal quantities $p_0, \rho_0, v_0, \phi_0, t_0, l_0, f_0, A_0$ for pressure, density, velocity, mass flux, time, length, mass flow and cross-sectional area respectively.

Then we can rewrite the governing equations in nondimensional variables $\bar{\rho}, \bar{t}, \bar{\phi}, \bar{x}, \dots$ through the substitutions $\rho = \rho_0 \bar{\rho}, t = t_0 \bar{t}, \dots$

Then

$$\frac{\partial \bar{\rho}}{\partial \bar{t}} + \left(\frac{\phi_0 t_0}{\rho_0 l_0} \right) \frac{\partial \bar{\phi}}{\partial \bar{x}} = 0$$

and

$$\frac{\partial \bar{\phi}}{\partial \bar{t}} + \left(\frac{p_0 t_0}{l_0 \phi_0} \right) \frac{\partial \bar{p}}{\partial \bar{x}} = - \frac{\lambda}{2D} \left(\frac{\phi_0 t_0}{\rho_0} \right) \frac{\bar{\phi} |\bar{\phi}|}{\bar{\rho}}$$

We use a *fixed* value for the speed of sound a , choose values for l_0, p_0, ρ_0, v_0 based on the data, and set $A_0 = 1, \phi_0 = \rho_0 v_0, t_0 = l_0 / v_0, f_0 = \phi_0 A_0$.

This choice of values reduces the governing equations to

$$\begin{aligned} \frac{\partial \bar{\rho}}{\partial \bar{t}} + \frac{\partial \bar{\phi}}{\partial \bar{x}} &= 0 \\ \frac{\partial \bar{\phi}}{\partial \bar{t}} + \frac{\mathcal{C}}{\mathcal{M}^2} \frac{\partial \bar{p}}{\partial \bar{x}} &= - \left(\frac{\lambda}{2D/l_0} \right) \frac{\bar{\phi} |\bar{\phi}|}{\bar{\rho}} \end{aligned}$$

where $\mathcal{C} = \frac{p_0}{\rho_0 a^2}$ and $\mathcal{M} = \frac{v_0}{a}$ are the Euler number and Mach number respectively. Note that in this process, the equation of state has never been considered. Thus, the non-dimensionalisation is valid for both ideal and non-ideal gas.

The ideal gas equation, $p = \rho R_g T$ transforms to $\bar{p} = \mathcal{C} \bar{p}$ since $a = \sqrt{R_g T}$. In non-isothermal problems, we can define a nominal temperature T_0 and set $a = \sqrt{R_g T_0}$ in that case to get $\bar{p} = \frac{\mathcal{C} T_0}{T} \bar{p}$.

For a non-ideal gas, assuming the CNGA equation of state we have $p \cdot (b_1 + b_2 p) = \rho R_g T$ which simplifies to the expression $\bar{p} = (\bar{b}_1 + \bar{b}_2 \bar{p}) \bar{p}$, where $\bar{b}_1 = \mathcal{C} b_1, \bar{b}_2 = \mathcal{C} p_0 b_2$.

The speed of sound a in a gas is given by $a^2 = \frac{dp}{d\rho}$. For an ideal gas, we get $a^2 = R_g T$, or in nondimensional terms $\frac{d\bar{p}}{d\bar{\rho}} = 1/\mathcal{C} = \bar{a}^2$.

For a simple CNGA equation, $p \cdot (b_1 + b_2 p) = \rho R_g T$, we can calculate the sound speed from $\frac{d\rho}{dp}$ since $\frac{dp}{d\rho} \cdot \frac{d\rho}{dp} = 1$. Thus $a_{CNGA}^2 = \frac{R_g T}{b_1 + 2b_2 p}$. Since $b_1 > 1, b_2 > 0, p > 0, a_{CNGA} < a$. We can reach the same conclusion from the fact that $\frac{d\bar{p}}{d\bar{\rho}} = \frac{1}{\bar{b}_1 + 2\bar{b}_2 \bar{p}}$ and $\bar{b}_1 > \mathcal{C}, \bar{b}_2 > 0$.

Let us record the CFL condition and its consequence next. Usually, it would be stated as $\bar{c}\Delta\bar{t}/\Delta\bar{x} \leq 1$, but to be safe, we consider $\bar{c}\Delta\bar{t}/\Delta\bar{x} \leq k$ for $k = 0.9$.

Note that $\bar{c} = \frac{\mathcal{C}}{\mathcal{M}^2} \sqrt{\frac{d\bar{p}}{d\bar{\rho}}}$. The CFL condition for the ideal gas is the strongest and thus it is sufficient to take $\bar{c} = \frac{\sqrt{\mathcal{C}}}{\mathcal{M}^2}$. For the particular choice $v_0 = a$, we get $\mathcal{C} = \mathcal{M} = \bar{c} = 1$.

Thus, for a given value of $\Delta\bar{t}$, $\Delta\bar{x} \geq \bar{c}\Delta\bar{t}/k$. Setting $\Delta\bar{x} = \bar{L}/m$, $m \leq \frac{\bar{L}k}{\bar{c}\Delta\bar{t}}$.

7. INCLINED PIPES

If the inclination of the pipes is taken into account, then gravity could have a component along the pipe, and if this is taken into account, the formulation needs to be modified slightly. For the given choice of non-dimensional variables, the momentum equation is modified to

$$\frac{\partial \bar{\phi}}{\partial \bar{t}} + \frac{\mathcal{C}}{\mathcal{M}^2} \frac{\partial \bar{p}}{\partial \bar{x}} = - \left(\frac{\lambda}{2D/l_0} \right) \frac{\bar{\phi}|\bar{\phi}|}{\bar{\rho}} + \left(\frac{l_0 g_{||}}{v_0^2} \right) \bar{\rho}$$

Given the elevation of the “from” and “to” ends of a pipe, $g_{||}$ can be calculated as the component of gravity along the assumed flow direction. The resultant nondimensional number $\mathbb{G}_{\text{pipe}} = \frac{l_0 g_{||}}{v_0^2}$ thus varies for each pipe, and is not a constant for the network.

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