Computational Model for Piping Systems and Valves Based on the Air Network Method: Postprint

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Abstract

The air network method, characterized by its rapid and practical features, is extensively employed in the computational research of aero-engine air systems for calculating various parameters at each cross-section of the air network. This methodology is applied to compressed air supply systems, which primarily comprise valves, pipelines, and local loss elements. As the original program lacked a valve calculation method, a valve computation model was first established. The flow characteristics of the valve were obtained experimentally, forming a computational method that was integrated into the air network program. A novel data structure was designed to represent the air network, and the program was re-implemented using an object-oriented language. The air network program was utilized to calculate pipeline flow rates and parameters at critical cross-sections under various valve opening conditions. Comparisons with experimental data revealed minimal deviations, thereby validating the accuracy and reliability of the computational method. Consequently, an air network model for compressed gas supply systems was developed and applied to pipeline system regulation and control. Air network calculations are performed to determine the required valve opening based on the gas flow rate and state parameters demanded by the test bench, enabling rapid valve adjustment to the desired position.

Full Text

Calculation Model of Tube System and Valve Based on Air Network Method

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Abstract: The air network method is widely used in aero-engine secondary air system research due to its computational efficiency and practical applicability for determining various parameters at each cross-section of the air network. This study extends the air network methodology to compressed air supply systems, which primarily consist of valves, pipelines, and local loss elements. Since the original program lacked a valve calculation method, a valve computation model was first established. The flow characteristics of the valve were obtained experimentally and incorporated into the air network program as a computational method. A novel data structure was designed to represent the air network, and an object-oriented program was redeveloped. The air network program was used to calculate pipeline flow rates and parameters at critical sections under different valve opening conditions. Comparisons with experimental values showed minimal deviation, thereby validating the accuracy and reliability of the computational method. The resulting air network model for compressed gas supply systems can be applied to pipeline system regulation. Air network calculations determine the required valve opening based on the gas flow rate and state parameters needed by the test facility, enabling rapid valve adjustment to the desired position.

Keywords: air network; valve; pipeline system; data structure

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Compressed air is an essential working fluid in aero-engine operation and serves as the medium in simulation experiments. In laboratory settings, compressed air supply systems deliver air with required mass flow rates and quality to test facilities. The design of such air supply systems should minimize flow losses while providing accurate and reliable service to the test facility. Valves, as critical components for flow regulation in pipeline systems, play a vital role. Adjusting valve opening yields different flow states within the system. Air network calculations determine the necessary valve opening, enabling rapid and precise adjustment. Therefore, air network computation for compressed gas supply systems holds significant practical value.

Researchers worldwide have conducted extensive studies using air network methods, primarily applying network approaches to engine air systems. Yannick et al. [?] performed comprehensive thermomechanical analysis of jet engine secondary air system models using open-source software CalculiX®, simulating the combined effects of flow characteristics and thermal-structural behavior in secondary air systems. Benra et al. [?] employed a one-dimensional air network model to simulate flow conditions in pre-swirl systems, comparing one-dimensional results with numerical and experimental data. Wu Dingyi [?] proposed a network computation method for internal flow systems with good computational stability and convergence. Hou Shengping et al. [?] developed a program for simulating unsteady characteristics of engine air systems. Guo Xiaojie [?] established a steady-state flow-thermal coupling analysis platform for aero-engine air systems and solid components by considering interactions between fluid properties (temperature, pressure, flow rate) and solid component thermal characteristics (temperature distribution). Lü Yaguo [?] developed general analysis software for engine air systems featuring graphical modeling for network generation and automatic network identification technology. Hu Xiaoxiao et al. [?] established continuity and energy equations using probabilistic concepts, developed a random walk model, and applied Monte Carlo methods to solve node pressures, then calculated fluid flow through each component based on the relationship between flow rate and pressure differential, achieving good agreement with Flowmaster results. Pan Yunfeng [?] obtained calculation methods for main components and established an air network model using a certain aero-engine as an example. Additional studies have applied air network methods to other applications. Lu Xiaolu [?] applied one-dimensional calculation methods to internal combustion engine performance simulation and developed simulation software. Zhang Guangpeng and Xu Nuo et al. [?] used Flowmaster for numerical simulation of an air conditioning system, demonstrating its positive guidance for HVAC design.

This paper applies the air network method to compressed gas supply systems, establishes a valve model, obtains characteristic parameters experimentally, and incorporates them into the air network program. Air network calculations are performed and compared with experimental results, enabling rapid determination of airflow parameters at critical pipeline sections.

1.1 Air Network Model

Based on the pipeline and valve arrangement in a laboratory compressed gas supply system, a corresponding air network model was simplified. [Figure 1: see original paper] shows the air network model for a laboratory compressed gas supply system, featuring one inlet, one outlet, six chambers, and ten branches. I1 represents the inlet, I2 the outlet, C1-C6 the six chambers, and E1-E43 the elements. The network contains three element types: tube elements, local loss elements, and valve elements, totaling 43 elements. lists the number of elements in each branch and the branch inlets/outlets.

The computational models and methods for these elements' flow resistance and heat transfer characteristics can be established through theoretical derivation, existing experimental data, and references, with models refined by comparing computational results with experimental data. The calculation methods for tube elements [?] and local loss elements [?][?] already exist in the air network program and have been validated through extensive use. This paper establishes the calculation method for valve elements, obtains the flow characteristics of laboratory valves through experiments, and incorporates the method into the air network program for engineering calculations of the entire network model.

1.2 Element Calculation Method

Valves are the most commonly used airflow regulation elements in wind tunnel systems. The control parameter for laboratory valve adjustment is opening degree. The laboratory employs electrically actuated valves—single-seat cage type with flow-to-open configuration. The fluid passing through the valve is compressible, resulting in two flow conditions for inlet total pressure calculation: choked flow and non-choked flow. Three parameters are introduced: F_K is the specific heat ratio coefficient (1.0 for air, $F_K = k/1.4$ for non-air media); X is the pressure differential ratio across the valve, defined as valve pressure drop Δp to inlet pressure p_1 ratio (since gas Mach number in pipelines is small, dynamic pressure is much lower than static pressure, making static pressure approximately equal to total pressure); X_T is the critical pressure differential ratio, a constant for a specific valve when choked flow occurs (0.75 for single-seat cage type with flow-to-open configuration).

When $X \geq X_T F_K$, choked flow occurs, and the inlet total pressure calculation formula [**?**] is:

$$Q_g = \frac{m}{\rho} \quad \text{(1-a)}$$

where y is the expansion coefficient, m is gas mass flow rate, ρ is gas density under standard conditions, K_v is the valve flow coefficient (defined as cubic meters of water at 5-40°C flowing through the valve in one hour under 10^5 Pa pressure drop), T_1 is valve inlet absolute temperature, G is gas relative density, Z is compressibility factor, and k is adiabatic index.

When $X < X_T F_K$, non-choked flow occurs, and the inlet total pressure calculation formula is:

$$\text{(1-b)}$$

where Q_g is gas volume flow rate under standard conditions.

From equation (1-a), when $X \geq X_T F_K$ (choked flow), the flow coefficient expression is:

$$K_v = \frac{Q_g}{\sqrt{\Delta p \cdot \rho}} \quad \text{(2-a)}$$

From equation (1-b), when $X < X_T F_K$ (non-choked flow), the flow coefficient expression is:

$$K_v = \frac{Q_g}{\sqrt{\Delta p \cdot \rho \cdot y}} \quad \text{(2-b)}$$

The right side of the flow coefficient expression contains dimensional parameters. Dimensional analysis of the flow coefficient was performed. shows the dimensional analysis results for parameters on the right side of equations (2-a) and (2-b). Based on these results and equations (2-a) and (2-b), the dimensions of the flow coefficient are $M^{1/2}L^{3/2}T^{-1}$. The flow coefficient varies with valve opening. In experiments, the flow coefficient values corresponding to different valve openings can be calculated from valve upstream/downstream pressures, flow rate through the valve, and upstream gas temperature.

1.3 Air Network Data Structure

Large air networks typically contain numerous elements with multiple inlets, outlets, chambers, and branches, forming highly complex graphical structures that require effective data organization for computer processing. Reference [**?**] defines inlet and outlet node numbers for each element, requiring strict consistency where the outlet node number of an upstream element matches the inlet node number of the downstream element. While conceptually simple, this approach is cumbersome for users who must be thoroughly familiar with numbering rules. Moreover, adding or removing a single element requires redefining nearly all node and element numbers to maintain sequential ordering from upstream to downstream.

To facilitate usage, a novel data structure is proposed. For the simplified air network model shown in [Figure 2: see original paper], branch-to-branch directed connections can be represented using a two-dimensional integer array as shown in , where array element $A[0][1] = 1$ indicates a directed connection from Branch 1 to Branch 2. This array, called the adjacency matrix, forms the top-level network data structure.

For individual branch data structures, as shown in [Figure 3: see original paper], each element contains two pointers, *pnext* and *plast*, linking different elements into a doubly linked list. Using class inheritance concepts from object-oriented programming [**?**], a standard class is derived into different element classes, enabling different element types to form a linear linked list. Users need only input parameters for each element in sequence without manual node numbering, as the computer automatically identifies and generates the linked list.

For individual element data structures, as shown in [Figure 4: see original paper], each element class contains function members and data members. The element calculation function *Cal_element(···)* is derived from the standard class, allowing a single function call for different element calculations during code implementation. Since data members are defined within the class, monitoring inlet/outlet parameter changes during debugging is convenient. In contrast, the original data structure defined different aerodynamic parameters in separate arrays indexed by node numbers, requiring constant array switching during debugging. Additionally, linked list data structures provide efficient memory usage.

2 Laboratory Valve Flow Characteristic Experiments

The compressed air used in the laboratory originates from a screw air compressor with maximum supply pressure of 0.7 MPa. Compressed gas stabilizes in a tank before entering the pipeline system. Pressure measurement employs pressure transmitters with 0-1 MPa range and 0.2 accuracy class. The sensor display outputs pressure readings, while also outputting 4-20 mA current signals converted to 1-5 V voltage signals via signal isolators, which are then acquired by an Advantech 4711A board into an industrial control computer. Temperature measurement uses K-type thermocouples with -40 to 1350°C range. Flow measurement employs a standard orifice plate throttling device combined with differential pressure transmitters, pressure transmitters, and thermocouples. The differential pressure transmitter has 0.1 accuracy class. The orifice plate differential pressure ΔP is measured by the differential pressure transmitter, orifice upstream pressure by the pressure transmitter, and gas temperature by the thermocouple.

The laboratory uses electrically actuated single-seat cage valves in flow-to-open configuration. This valve' s flow characteristics must be determined experimentally. The experimental setup includes pressure sensors upstream and downstream of the electric valve, a K-type thermocouple upstream, and an orifice flow meter downstream.

From equation (1-a), when $X \geq X_T F_K$ (choked flow), the flow coefficient expression is equation (2-a). From equation (1-b), when $X < X_T F_K$ (non-choked flow), the flow coefficient expression is equation (2-b).

3.1 Valve Flow Coefficient Characteristic Curves

Valve flow characteristics primarily vary with opening degree. Experiments were conducted at three supply pressures: 0.7 MPa, 0.5 MPa, and 0.35 MPa. [Figure 5: see original paper] shows the experimental results, with three curves representing flow coefficient curves at different supply pressures. The three curves are similar and conform to the valve' s equal percentage characteristic curve. The average flow coefficient values at each opening under different supply pressures yield the expression $y = 157.480x^2 + 45.915x + 7.002$, which is incorporated into the program for calculations.

3.2 Network Calculation Results and Experimental Comparison

Air network modeling calculations for the pipeline system were performed by adjusting valve opening to create different operating conditions. Input files for the air network program were written and computations executed for each condition.

First, for supply pressure of 0.7 MPa (gauge) with the electric valve in branch 5 at 0.15 opening. [Figure 6: see original paper] compares air network program results with experimental measurements. Relative deviation between calculated and experimental values is used to assess accuracy, defined as the absolute difference between calculated and experimental values divided by the experimental value. Pressure was measured at four points in the network, with maximum deviation of 3.2% and minimum deviation of 0.2%. Flow rate deviation between calculated and measured results was 4.1%.

Second, for supply pressure of 0.7 MPa (gauge) with the valve opening at 0.8. [Figure 7: see original paper] compares program results with experimental measurements. Pressure loss at the valve is smaller than at 0.15 opening. Pressure comparison shows maximum relative deviation of 0.6% and minimum of 0.1%. Flow rate deviation is 3.9%.

Third, for supply pressure of 0.5 MPa (gauge) with valve opening at 0.8. [Figure 8: see original paper] compares program results with experimental measurements. Pressure comparison shows maximum deviation of 2.3% and minimum of 0.4%. Flow rate deviation is 6.9%.

compares calculated and experimental flow rates at 0.7 MPa supply pressure for various valve openings. Maximum relative deviation occurs at 0.2 opening (10.47%), attributed to small flow values at low openings where minor calculation errors produce large relative deviations, combined with flow measurement errors and minor pipeline leakage to the environment.

compares flow rates at 0.5 MPa supply pressure. Larger relative deviations occur at small openings, with maximum deviation of 12.24% at 0.2 opening.

compares flow rates at 0.35 MPa supply pressure. Larger deviations occur at small openings, reaching 11.8% maximum at 0.3 opening. Overall, relative deviations between network calculations and experimental measurements are below 10% for most operating conditions and below 13% for all cases, validating the accuracy and reasonableness of the air network model and computational method.

4 Conclusions

This study investigates a laboratory compressed gas supply system using the air network method. An air network model was established, computational methods and element flow characteristics were refined through experiments, and one-dimensional air network calculations were performed. The main conclusions are:

1) The air network method was applied to compressed gas supply systems with a dedicated network model incorporating valves, local losses, and pipelines. A novel data structure was proposed for air network organization using a three-tier architecture of graphical structure-linked list-class, which facilitates user operation and saves computer memory.

2) Valve elements were calculated using a one-dimensional method. Valve flow characteristics were obtained experimentally, yielding flow coefficient variation curves with opening degree. The computational method and flow coefficient curves were incorporated into the air network program.

3) One-dimensional calculations of the entire air network were performed and compared with experimental measurements. At supply pressures not

exceeding 0.7 MPa, relative deviations for both pressure and flow rate were small, validating the accuracy and reliability of the computational method. Research on one-dimensional calculation models for compressed air pipeline systems provides comprehensive understanding of system flow characteristics and enables rapid valve regulation during experiments.

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Note: Figure translations are in progress. See original paper for figures.