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

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Abstract

The air network method, owing to its rapid and practical characteristics, calculates various parameters at each cross-section of the air network and has been widely applied in computational research of aero-engine air systems. The concept of the air network method is applied to compressed air supply systems, which primarily include valves, pipelines, local losses, and other major components. Since the original program lacked a valve calculation method, a computational model for valves was first established, the flow characteristics of valves were obtained through experiments, a calculation method was formulated, and it was incorporated into the air network program. A novel data structure was designed to represent the air network, and an object-oriented language program was rewritten. The air network program was employed to calculate pipeline flow rates and parameters at critical cross-sections under various valve opening conditions; comparison with experimental values showed minimal deviation, thereby verifying the accuracy and reliability of the calculation method. Consequently, an air network model for the compressed gas supply system was obtained and applied to pipeline system regulation. Air network calculations are performed to determine the required valve opening based on the gas flow rate and state parameters required by the test bench, enabling rapid adjustment of the valve 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, known for its rapid and practical characteristics, is widely used in aero-engine secondary air system calculations to determine various parameters at each cross-section. This methodology is applied to compressed air supply systems, which primarily consist of valves, pipes, 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, forming a calculation method that was incorporated into the air network program. A novel data structure was designed to represent the air network, and an object-oriented program was rewritten. The air network program was used to calculate flow rates and parameters at critical sections under different valve opening conditions. Comparisons with experimental values showed minimal deviation, thereby verifying the accuracy and reliability of the calculation 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; Tube system; Data structure

Compressed air is an essential working fluid in aero-engine operation and 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 key components for regulating airflow in pipeline systems, play a crucial role. Adjusting valve opening yields different airflow states within the system. Air network calculations determine the necessary valve opening for rapid and precise adjustment. Therefore, air network computation for compressed gas supply systems holds significant practical value.

Researchers worldwide have extensively applied air network methods, primarily to engine air systems. Yannick et al. [?] performed integrated thermomechanical analysis of jet engine secondary air systems using open-source software CalculiX®, simulating the combined effects of flow characteristics and thermal-structural behavior. 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 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 thermal characteristics (temperature distribution). Lu 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 nodal pressures, then calculated component flow rates based on pressure differences, showing good agreement with Flowmaster. Pan Yunfeng [?] obtained calculation methods for main components and established an air network model for a specific aero-engine type. Other studies have applied air network methods to different fields: Lu Xiaolu [?] applied one-dimensional methods to internal combustion engine performance simulation and developed simulation software; Zhang Guangpeng and Xu Nuo et al. [?] used Flowmaster for HVAC system numerical simulation, demonstrating its positive guidance for HVAC design.

This paper applies the air network method to compressed gas supply systems, establishing a valve model and obtaining characteristic parameters through experiments for integration into the air network program. Network calculations were performed and compared with experimental results, demonstrating that one-dimensional calculations can rapidly determine airflow parameters at critical pipeline sections.

1.1 Air Network Model

Based on the layout of pipes and valves 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 this 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 and inlet/outlet information for each branch in the air network.

The calculation models and methods for these elements' flow resistance and heat transfer characteristics can be established through theoretical derivation, existing experimental data, and references, then improved by comparing calculations 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 flow characteristics of the laboratory valves through experiments, and incorporates these methods into the air network program for comprehensive engineering calculations of the entire network model.

1.2 Component Calculation Methods

Valves are the most commonly used airflow regulation elements in wind tunnel systems. The control parameter for laboratory valves is opening degree. The electrically-driven valve used in the laboratory is a single-seat cage type with flow-to-open configuration. Since the fluid passing through the valve is compressible, inlet total pressure calculations must account for both choked and non-choked flow conditions. Three key parameters are introduced: F_K is the specific heat ratio coefficient (taken as 1 for air, $F_K = k/1.4$ for non-air media); X is the pressure differential ratio across the valve, defined as the ratio of valve pressure drop Δp to inlet pressure p_1 (since gas Mach number in the pipe is very small, dynamic pressure is much lower than static pressure, so static pressure approximates total pressure); X_T is the critical pressure differential ratio, a constant for a specific valve when choked flow occurs, taken as 0.75 for single-seat cage type flow-to-open configuration.

When $X \geq X_T F_K$, choked flow occurs and the inlet total pressure is calculated as:

(1-a)

where Q_g is the volumetric flow rate under standard conditions ($Q_g = m/\rho$), 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 absolute temperature at valve inlet, G is gas relative density, Z is compressibility factor, and k is adiabatic index. The expansion coefficient y is given by:

$$y = \text{[expression]}$$

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

(1-b)

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 method is cumbersome for users who must master the numbering rules, and 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 is called the adjacency matrix, representing the top-level network data structure.

At the branch level, as shown in [Figure 3: see original paper], each element contains two pointers, p_{next} and p_{last}, linking different elements into a doubly-linked list. Using class inheritance principles from object-oriented programming [**?**], a standard base 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.

At the element level, 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, unlike the original data structure where different aerodynamic parameters were defined in separate arrays indexed by node numbers, requiring constant array switching during debugging. Additionally, linked list 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. Sensor displays show pressure readings, while 4-20 mA current signals are converted to 1-5 V voltage signals via isolators and collected by an Advantech 4711A board into an industrial control computer. Temperature measurement uses K-type thermocouples with -40 to 1350°C range. Flow measurement utilizes a standard orifice plate with differential pressure transmitter, pressure transmitter, and thermocouple. The differential pressure transmitter has 0.1 accuracy class, measuring orifice pressure difference ΔP, upstream pressure, and gas temperature.

The electrically-driven valve used is a single-seat cage type in flow-to-open configuration, with flow characteristics determined experimentally. The experimental setup includes pressure sensors upstream and downstream of the valve, a K-type thermocouple upstream, and an orifice flowmeter downstream.

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

(2-a)

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

(2-b)

Dimensional analysis of the flow coefficient is performed since parameters on the right side have dimensions. shows the dimensional analysis results for equations (2-a) and (2-b), revealing the flow coefficient dimension as [dimension]. The flow coefficient varies with valve opening. Experiments calculate the flow coefficient at different openings based on valve pressure differential, flow rate, and upstream temperature.

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] presents the experimental results, showing three flow coefficient curves corresponding to different supply pressures. The curves are similar and follow the valve' s equal percentage characteristic. The average flow coefficient across different pressures yields the expression $y = 157.480x^2 + 45.915x + 7.002$, which is incorporated into the program.

3.2 Network Calculation Results vs. Experimental Comparison

Air network modeling calculations were performed for the pipeline system under various valve opening conditions. Input files were created for different operating conditions and computed.

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

For supply pressure of 0.7 MPa with valve opening of 0.8, [Figure 7: see original paper] shows the comparison. Pressure loss at the valve was smaller than at 0.15 opening. Maximum pressure deviation was 0.6% and minimum 0.1%, with flow rate deviation of 3.9%.

For supply pressure of 0.5 MPa with valve opening of 0.8, [Figure 8: see original paper] presents the comparison. Maximum pressure deviation was 2.3% and minimum 0.4%, with flow rate deviation of 6.9%.

compares calculated and experimental flow rates at 0.7 MPa supply pressure. The maximum relative deviation of 10.47% occurred at 0.2 opening because small flow rates amplify relative deviations from minor calculation errors, combined with flow measurement errors and minor pipeline leakage to the environment.

shows comparisons at 0.5 MPa supply pressure, where larger deviations occurred at small openings, reaching 12.24% at 0.2 opening.

presents comparisons at 0.35 MPa supply pressure, showing larger deviations at small openings with maximum deviation of 11.8% at 0.3 opening. Overall, relative deviations between network calculations and experimental results are mostly below 10%, with a few cases below 13%, validating the accuracy and reasonableness of the air network model and calculation methods.

4 Conclusions

This study investigates a laboratory compressed gas supply system using the air network method. An air network model was established, calculation methods and component 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 pipes. 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. Experimental data provided valve flow characteristics in the form of flow coefficient versus opening curves, which 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 up to 0.7 MPa, relative deviations for both pressure and flow rate were small, verifying the accuracy and reliability of the calculation method. The one-dimensional calculation model for compressed air pipeline systems provides comprehensive understanding of system flow characteristics and enables rapid valve regulation during experiments.

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