Journal of Marine Science and Technology

Volume 25 | Issue 1 Article 8

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Horng, Wen-Kong and Shaw, Heiu-Jou (2017) "A STUDY ON THE INTEGRATED DESIGN OF ENGINE ROOM VENTILATION," *Journal of Marine Science and Technology*: Vol. 25: Iss. 1, Article 8.
DOI: 10.6119/JMST-016-0913-1
Available at: https://jmstt.ntou.edu.tw/journal/vol25/iss1/8

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Journal of Marine Science and Technology, Vol. 25, No. 1, pp. 70-83 (2017)
DOI: 10.6119/JMST-016-0913-1

A STUDY ON THE INTEGRATED DESIGN OF ENGINE ROOM VENTILATION

Wen-Kong Horng and Heiu-Jou Shaw

Key words: ventilation design, engine-room arrangement, three-dimensional design.

ABSTRACT

This paper presents a ventilation system design process that integrates the key plan and working plan design phases using evolving 3D models to reduce the required number of design man-hours. The process is called the Routing-Expanding-Predicting Ventilation (REPV) process. First, the routes of a ventilation system are determined based on a 3D model of the ship engine room, and the dimensions of the rectangular ventilation ducts are expanded to maintain a range of air velocities using the Duct Route Arrangement program (DRAP) in the key design phase. Finally, after the routes of the ventilation models are revised in the working design phase, the air quantities that are deliverable at the duct outlets are predicted using the Flow Rate Analysis Program (FRAP); these two programs can be replaced by many other ventilation analysis methods/programs. The REPV design process is demonstrated using a 4622 TEU container ship, which is driven by a diesel engine, and the predicted flow rates are compared with measurements taken in the ship engine room.

I. INTRODUCTION

The engine room of a ship is a structure fitted with machinery equipment sets (including main propulsion engine, auxiliary engines, tanks, etc.) and associated ventilation, cable, and piping systems to ensure that the ship can continue to provide transportation functions. The purposes of the ventilation systems are to provide sufficient air for engine combustion and to discharge heat produced by the engines so that engine functions are not interrupted (BS EN ISO 8861, 1998). Therefore, a precise and effective design approach for ventilation systems is very important for ship design.

In general, the design and manufacturing process of engine room ventilation systems is divided into three phases: key plan design, working plan design, and construction. In the key plan design phase of the engine room, two of the primary concerns are the arrangement of the equipment sets and associated systems and the completion of the design diagrams, including the Engine Room Machine Arrangement (Kim et al., 2009), Piping System Diagrams (Kang et al., 1999), Cableway Diagrams (CSBC, 2012), Ventilation Diagrams (Wu et al., 2012), etc.

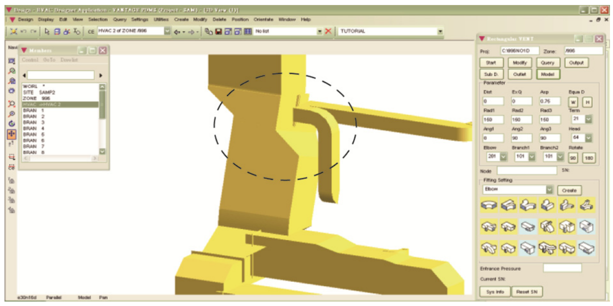

Fig. 1. Ventilation model for preliminary design in the key plan stage.

The key plan design of ventilation systems cannot be started until the arrangement of the equipment sets in each individual engine room space has been completed. The main context of the key plan design phase of the ventilation systems is to determine the functions of the systems, including assigning the air flow rates that supply individual spaces/zones, laying out the ventilation duct routes, and determining the circular diameters of the ventilation ducts.

In the key plan design phase, the first step in the ventilation system design is to assign the positions and air flow rates of the ventilation outlets. Then, the routes of the ventilation ducts from the forced draft fans should be designed, which is followed by determining the types of ventilation duct components. The circular diameter of each duct component can then be determined using computer-aided ventilation system design programs (Lee and Chen, 1991; Yang et al., 2004; Wu et al., 2012).

Theoretically, three-dimensional (3D) ventilation duct models can be constructed based on the above information (duct components, positions, and orientations). However, traditionally, only a few types of ventilation duct component are used during the key plan design phase. Several branching devices of the ventilation ducts could be connected at the same position (Fig. 1). Such a situation will be modified during the working plan design phase. For instance, the ventilation duct model shown in

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Table 1. Summary of ventilation system design methods.

Design method	Pressure balance	Applications and Properties
Equal Velocity Method	×	1. Often for exhaust ventilation system 2. Minimum velocity to carry dust is important 3. Limit velocity to reduce noise
Equal Friction Method	×	1. Most widely used in normal HVAC applications 2. Duct friction loss per unit length remains constant 3. Suited for symmetric duct arrangements
Static Regain Method	×	1. Normally used with a computer package for high-velocity systems 2. Air duct is sized such that an increase in the static pressure nearly offsets the static pressure loss of the succeeding duct section along the main duct
T-Method	✓	1. Optimizing procedure by minimizing life-cycle costs 2. System condensing (into a single imaginary duct) 3. Fan selection (optimum system pressure loss) 4. System expansion (back to original duct system)

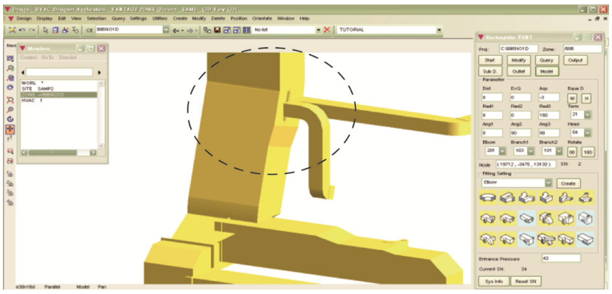


Fig. 2. Manually modified ventilation model in the working design stage.

Fig. 1 will be modified to the one shown in Fig. 2.

The working plan design phase is to determine the cross-sectional dimensions of the rectangular ducts converted from circular ones and to adjust the positions and orientations of the outlets of the ventilation systems.

In addition, once the ventilation system design moves to the working plan phase, the 3D piping, cable, and ventilation models will be merged into a single set of engine room arrangement and structure models. Ventilation duct routes could be modified when the ducts interfere with structural members or piping and cable systems.

At this point, instead of recalculating the diameters of the ventilation ducts (like the design work done in the key plan phase), some shipyards simply choose to increase the capacities of the forced draft fans to ensure that the air flow rates delivered through the modified ventilation systems are higher than required. Thus, (1) the air flow rates to be delivered by the ventilation systems that are modified in the working design phase are not checked against the design requirements, (2) the flow rates delivered by the modified (and constructed) ventilation systems remain unknown until sea trails, and (3) the initial costs of the draft fans will be increased without checking whether it is necessary.

This research has developed a new ventilation system design process that (a) applies the Balanced-Capacity Method (McQuiston and Parker, 1994) in different modes to determine the diameters of the ducts and to predict the air quantity delivered by the ventilation system (to ensure the air deliveries of the ventilation systems satisfy the design requirements) and (b) uses rectangular ducts throughout the key plan and working plan design phases.

The advantages of applying such a design process and method include (1) the working plan design phase uses the 3D ventilation system model layouts in the key plan design phase, (2) the ventilation models developed in the working plan design phase would be very similar to the ventilation system finally constructed, and, most importantly, (3) the air quantities delivered by the ventilation systems that are modified in the working design phase can be predicted.

II. LITERATURE REVIEW

Commonly used ventilation system design methods include the Equal Velocity Method, Equal Friction Method, Static Regain Method, and T-Method (ASHRAE Handbook). The first three methods are simple but do not guarantee a balance of the total pressure at the outlets of the ventilation system. Table 1 compares the ventilation methods.

The Equal Velocity Method assumes a selected uniform velocity for each duct segment in the ventilation system. The dimensions of the duct segments are determined based on the air flow rate and the velocity. There is an upper bound on the velocity due to limits on noise and a lower bound that ensures that no particles or dust deposit in the ducts. Design adjustment efforts and additional device costs are unavoidable when balancing the total pressure at the outlets. The Equal Velocity Method has been applied in semiconductor factories (Chen, 2001). It has been proposed to resolve the pressure imbalance induced by the velocity method using the feedback design of the T-Method. Reduction inaccuracy between design and both operation and process safety of the exhaust system is achieved.

In the Equal Friction Method, the frictional (pressure) loss per unit length of the duct (Pa/m) is held constant. The frictional losses can be caused by the viscosity and turbulence of the air flow through the ducts and by the dynamic pressure loss in the fittings (such as dampers), which change the airflow direction or area. The dynamic pressure loss is also expressed in terms of the equivalent length of the duct. The equal frictional loss is achieved through iteration, and better balance in total pressure can be obtained by adjusting the duct size (smaller size for larger velocity and pressure loss). Such a design method is best suited for symmetric duct arrangements because balance in the total pressure is difficult to achieve when the variation in the equivalent duct lengths is large.

The Static Regain Method is based on the Bernoulli Equation. The total energy required for the ventilation system remains relatively low, assuming that the ventilation system can gain static pressure from the reduction in velocity (thus, a loss in dynamic pressure). However, from a fluid mechanics perspective, this design method is not appropriate for ventilation system design due to the following facts: the Bernoulli principle cannot be applied to branching ducts, balance in the total pressure at the outlets is not obtainable, the static pressure regain factors are difficult to determine, and energy savings cannot be achieved by converting dynamic pressure to static pressure.

However, the T-Method (Tsal et al., 1986, 1988), which minimizes the electric power of the fan and the manufacturing and life cycle costs of the ventilation system, can balance the total pressure at the outlets through complicated mathematic formulations and computer iterations. Its design process includes system condensing, selection of ventilation fans, and system expansion. The drawback of the T-Method is that it is very difficult to have the design point (the combination of the ventilation velocity and discrete duct dimensions) fall beneath the property curve of the ventilation fan.

The Balanced Capacity Method used in this research is a variation of the Equal Friction Method. The basic design principle of this method is to hold the total pressure loss equal for all duct routes (from the fan to the outlets) and to satisfy the required air quantities discharged at the outlets (McQuiston and Parker, 1994). This method begins with the calculation of the total pressure loss and the pressure loss per unit length for the route of the longest equivalent length. For any other route, the diameter will be reduced to obtain the necessary velocity to increase the loss in total pressure, as long as the noise limits are not violated. Thus, the duct size and use of dampers in the ventilation system will be reduced in the ventilation systems designed using this method.

In the development of computer-aided engine room ventilation system design, Lee and Chen (1991) expressed ventilation duct routes as interconnected line segments (which were defined by end point coordinates) and calculated the diameters of the ventilation ducts. The ventilation routes were drawn using AutoCAD (2013). Yang et al. (2004) developed a method to express the ventilation routes as isometric drawings and allow designers to assign a numerical identification for each segment of ventilation duct to reduce human errors. Optimal ventilation system design and the development of computer models of ventilation systems were proposed (Wu et al., 2012). These steps were important for engine room design in the past.

The Equal Friction Method has been used in the design of ventilation systems for a long time. When using this method in ventilation system design, the frictional (pressure) loss per unit length of the duct (Pa/m) is held constant. The frictional losses can be caused by the viscosity and turbulence of the airflow through the ducts and by the dynamic (pressure) loss in fittings that change the air flow direction or area (such as dampers). The dynamic loss is expressed in terms of equivalent length of the duct.

A variation of the Equal Friction Method is the Balanced Capacity Method. The basic design principle of the Balanced Capacity Method is to hold the total pressure loss equal for all duct routes (from fan to outlets) and to satisfy the required air quantities discharged (McQuiston and Parker, 1994). This method begins with calculating the total pressure loss and the pressure loss per unit length for the route with the longest equivalent length. For any other route, the diameter will be reduced to obtain the necessary velocity to increase the total pressure loss, as long as the noise limitations are not violated. Therefore, the duct size and use of dampers in the ventilation system will be reduced in ventilation systems designed using this method.

III. VENTILATION SYSTEM DESIGN PROCESSES

1. Existing Process

A flow diagram of the engine room ventilation system design process currently used in a large shipyard is shown in Fig. 3. In this process, once the body plan of the engine room sections is given, designers can roughly recognize the space of the engine room and the total number of decks. Based on the specified functions of equipment sets, their positions can be assigned. Then, the height of each deck can be determined by considering the heights and maintenance space of the equipment sets as well as the required operation and walking spaces. As a result, the engine room machine arrangement can be preliminarily outlined in a 2D drawing (see Fig. 3, the Eng. Rm. Design Info. Step).

This preliminary engine room machine arrangement is the basis for the ventilation system diagrams, which is one of the outputs of the key plan design phase of ventilation systems. The first step of this phase is to determine the capacities of the forced draft fans and the preliminary arrangement of the ventilation duct routes (see Fig. 3, the 2D CAD Key Plan Step). Each deck of the engine room will be divided into several (most commonly four) regions, the sum of the air flow rates required for equipment sets in a region will be calculated to determine the total capacities of each fan and the total number of fans.

The second step of the key plan design of the ventilation system is to determine the diameters of the ventilation duct segments. Each equipment set (including tanks) that requires air

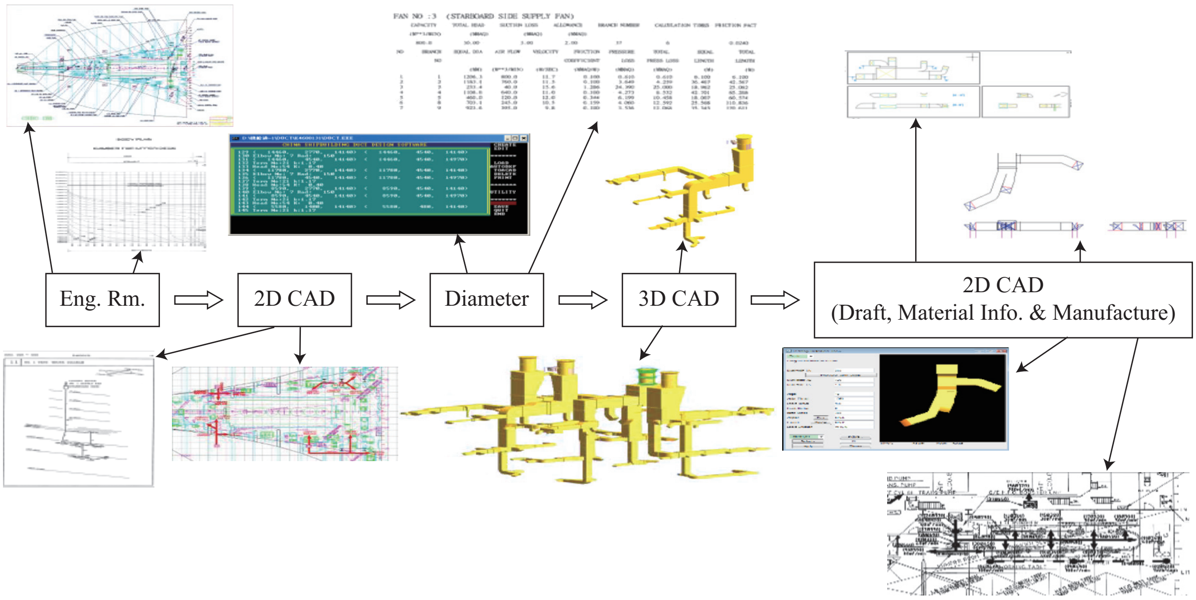


Fig. 3. Steps and model generated in the existing design process.

for heat radiation, combustion, or operation will be treated as a node. These air quantity deliveries are the design requirements of the ventilation systems.

Nodes close to each other can share a ventilation outlet. This outlet has an air quantity requirement that is the sum of these nodes. The capacity of a draft fan is the sum of the air quantities of the ventilation outlets connected to the fan. Because thin ducts next to each other can be merged into a larger duct, the merged ventilation ducts and outlets form the ventilation route and system.

With known ventilation routes and air quantities at the outlets, the diameters of each duct segment can be determined in the key plan design phase using the Equal Friction Method (see Fig. 3, the Diameter Calculation Step) and assuming that the cross section of the duct is circular and the diameters are the same.

In the working plan design phase, the cross section of the duct will be modified from circular to rectangular (see Fig. 3, the 3D Working Plan Step), and the ventilation route could be modified considering the engine room structure, piping systems, cableway arrangements, and heights of the ventilation ducts (for instance, 2.1 meters from the floor).

Finally, the manufacturing and construction drawings of the ventilation systems are generated according to the results of the working plan design (see Fig. 3, the 2D CAD Manuf. & Constr. Drawing Step); however, minor modification could occur due to interference encountered in the construction process or the addition of new equipment sets or outlets.

The drawback of the existing ventilation design process described above is that although the cross sections of the ventilation ducts, ventilation routes, and even the total number of ventilation ducts are allowed to change in the working plan design phase, the air quantities delivered by the modified ventilation systems are not checked to ensure that they still satisfy the design requirements. Furthermore, modifications of the ventilation ducts could occur in the construction process, and in general, design engineers are not informed about such modifications. In such a shipyard situation, no one could know whether the final constructed ventilation systems can satisfy the design requirements.

2. New Process

This research developed a new ventilation system design process in which 3D rectangular ducts are used directly in the key plan design phase (see Fig. 4, the Eng. Rm. Design Info. Step) throughout the entire design modeling process. We implement a prototype of the new process using a 3D model of the database from the AVEVA Plant Design Management System (PDMS), which is a representative CAD system for shipbuilding. The advantage of using a 3D model is that the input data to the analysis code could be generated from the CAD models, instead of entered manually.

In the new design process, the second step of the key plan design phase represents the route of the ventilation system as 3D ducts with uniform rectangular cross sections using PDMS (See Fig. 4, the 3D CAD Key Plan Step). The air quantity deliveries will be assigned. Next, the routes and cross section dimension information will be extracted from the PDMS model for Duct Analysis I to determine the new dimensions of the ducts, based on the ventilation route and air quantity delivery requirements (see Fig. 4, the Diameter Calculation Step). Third, the dimensions of the ventilation system PDMS model will be modified accordingly, and traditional ventilation system diagrams can be generated in AutoCAD format, if needed.

In the working plan design phase, first, the dimensions of the ventilation system will be expanded using Duct Analysis II

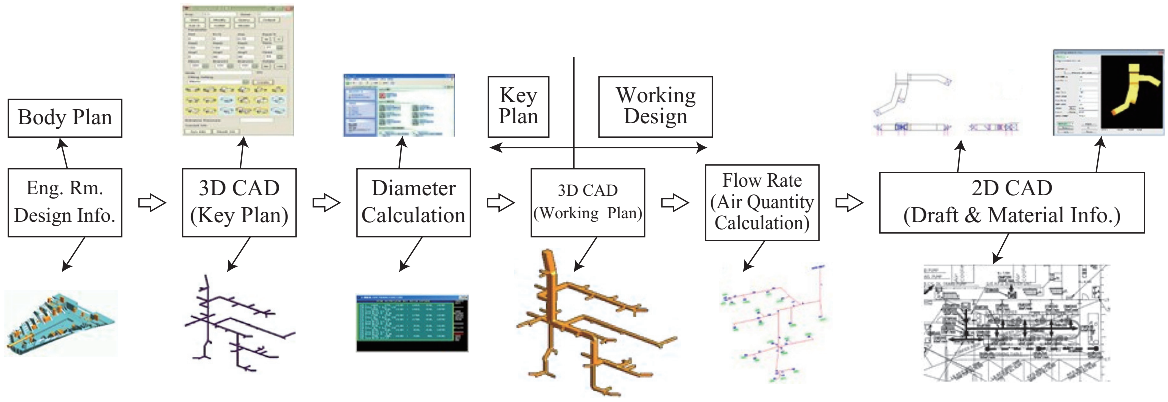


Fig. 4. Steps and model/information generated in the new design process.

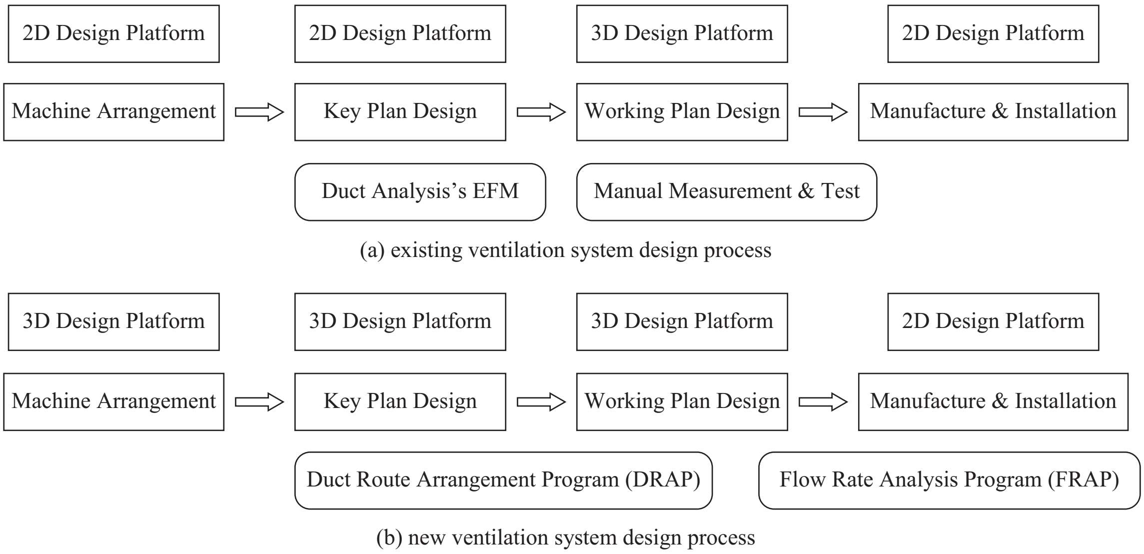


Fig. 5. 2D and 3D design platforms and analysis methods used in the existing and new processes.

(see Fig. 4, the 3D CAD Working Plan Step). Then, the ventilation duct routes could be modified to avoid interference between the ducts and other systems, such as structural members, pipes and cable racks. Next, the air quantity delivery of the system will be checked through Flow Rate Analysis (see Fig. 4, the Flow Rate Analysis Step) based on the modified ventilation route and given cross sectional dimensions of the ducts. Finally, if the air quantity delivery does not satisfy the requirements, the Flow Rate Analysis will be used again to determine the new dimensions of the ducts.

Similar to the existing process, once the design of the 3D model of the ventilation systems is completed, the manufacturing and construction drawings of the duct system will be generated from the PDMS CAD models (see Fig. 4, the 2D CAD Manuf. & Constr. Drawing Step).

The Duct Analysis I, Duct Analysis II, and Flow Rate Ana-]lysis programs mentioned above are three application modes of the Balanced-Capacity Method. Details of these three analyses are presented in Section 4.

Figs. 5(a) and (b) illustrate the 2D and 3D software platforms used along the process flows of the existing process and the new process, respectively, where the Equal Friction Method (EFM) and Balanced-Capacity Method (BCM) are used, respectively.

Using the new process, engineers can ensure the satisfaction of the (air quantity) design requirements and can migrate ventilation system design from the original to modified designs in the key plan design and working plan design phases. The drawbacks of the existing design process will be fixed in the new process.

IV. DESIGN CALCULATION AND VERIFICATION

1. Balanced-Capacity Method and Example

The steps to determine duct diameters using the iterative approach of the Balanced Capacity Method are described below (ASHRAE, 2009a, 2009b):

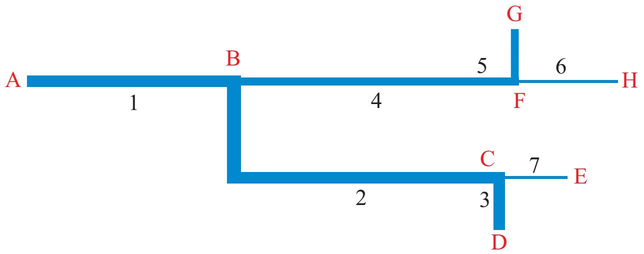


Fig. 6. Example of a ventilation system.

(a) Determine the air flow rate of each duct sitting between the draft fan and outlets based on the flow rates at the outlets of the ventilation system. For each duct, assign an initial diameter guess, which will be replaced by new value determined in the next iteration.
(b) Similar to the Equal Friction Method, find the longest duct route (from the draft fan to an outlet), where fittings and branches are converted to equivalent lengths of ducts, and calculate the pressure drop per unit length of the longest duct route. The length of a duct route is the sum of the lengths of the straight ducts, fittings, and branches.
(c) Calculate the total pressure at each branching point of the longest duct route.
(d) Among the branch routes that start from the branching points of the longest duct route, find the longest duct route of the branch routes. Similar to Step (b), calculate the pressure drop per unit length of the longest branching route based on the total pressure at the branching point (determined in Step (c)), and determine the total pressures at the branching points of the longest branching route.
(e) Continue the calculation of the pressure drop per unit length (similar to Step (d)) until the pressure drop per unit length of each branch has been determined.
(f) Continue the iteration (from Steps (c) to (e)) until the convergence criterion is satisfied.

The iterative approach of the Balance-Capacity Method developed in this research to determine the diameters of the ducts in a given ventilation system and deliver assigned flow rates at the outlets is explained using a simple ventilation system shown in Fig. 6. There are 4 outlets (D, E, G, and H) and 4 routes (L_{123}, L_{127}, L_{145}, and L_{146}) in the ventilation system. According to the length calculation, route L_{123} is the longest, which has branching points at B and C. Next, define any duct, called the *i*-th duct, as a path between two neighboring outlets, such as the 1-th, 2-th, …, 7-th duct. All ducts are shown in Fig. 6.

Assume the air flow rates in the 3 ducts of route L_{123} are Q_1, Q_2, and Q_3, respectively. The diameters of these ducts are D_1, D_2, and D_3, and the total pressures drops in these ducts are ΔP_1, ΔP_2, and ΔP_3, respectively.

Eqs. (1) to (4) describe the relationship between Q_i, D_i, V_i and the pressure drop per unit length dhu_i.

$$D_i = \left(0.00187 \times \frac{Q_i^{1.9}}{dhu_i}\right)^{\frac{1}{5.02}} \tag{1}$$

$$Q_i = A_i V_i = \frac{\pi D_i^2}{4} V_i \tag{2}$$

$$V_i = \frac{4Q_i}{\pi D_i^2} \tag{3}$$

$$dhu_i = \frac{\Delta P_i}{L_i + L_{ie}} \tag{4}$$

where L_{ie} is the sum of equivalent lengths of branches and fittings in the *i*-th duct. The relationship between total pressure loss ΔP_i, velocity V_i, duct length L_i and L_{ie} is described in Eq. (5), where *f* is the friction factor and *C* is the local loss coefficient in the duct.

$$\begin{aligned}
\Delta P_i &= \Delta P_{if} + \Delta P_{id} \\
\Delta P_i &= \left(f \frac{L_i}{D_i} + \sum C\right)\left(\frac{\rho V_i^2}{2}\right) \\
\Delta P_i &= \left(f \frac{L_i + L_{ie}}{D_i}\right)\left(\frac{\rho V_i^2}{2}\right) \\
\Delta P_i &= \left(f \frac{L_i + L_{ie}}{D_i}\right)\left(\frac{8\rho Q_i^2}{\pi^2 D_i^4}\right)
\end{aligned} \tag{5}$$

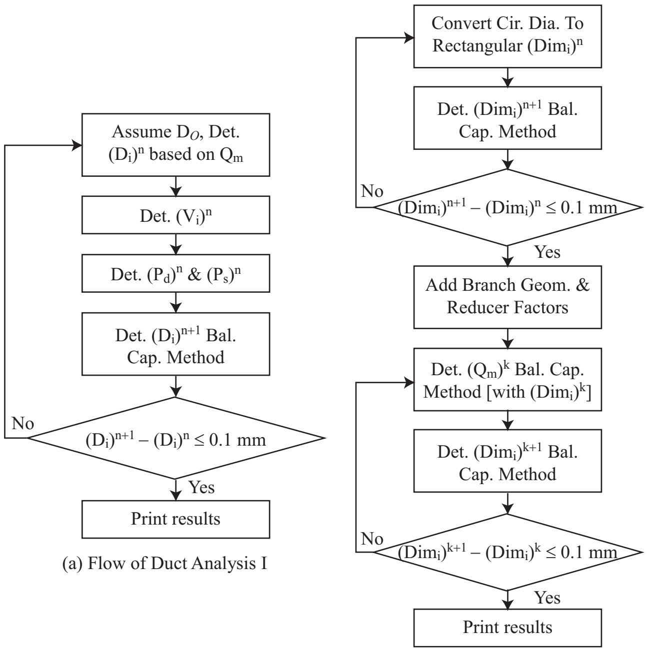
According to the Balanced-Capacity Method, the total pressure at outlets D and E (or the drops in total pressure in routes L_{123} and L_{127}) are the same. Because ducts L_3 and L_7 are branched from the same tail position on duct 2 and each of them is connected with an outlet, the total pressure drops of these two duct segments (ΔP_3 and ΔP_7) should be the same. Thus, the pressure drop per unit length of duct L_7 can be calculated according to Eq. (6), and the diameter of duct L_7 can be determined using Eq. (1).

$$dhu_7 = \frac{\Delta P^3}{L_7 + L_{7e}} \tag{6}$$

Once the diameters of the longest route L_{123} and its branch L_{127} are known, the same approach is used for routes L_{145} and L_{146}.

In the example, the air flow rate at outlets D, E, G, and H (i.e., Q_3, Q_5, Q_6, and Q_7) are given; thus, the flow rates in the remaining ducts 1, 2, and 4 (i.e., Q_1, Q_2, and Q_4) can be derived using Eq. (7).

$$\begin{aligned}
Q_2 &= Q_3 + Q_7 \\
Q_4 &= Q_5 + Q_6 \\
Q_1 &= Q_2 + Q_4 = Q_3 + Q_5 + Q_6 + Q_7
\end{aligned} \tag{7}$$



(a) Flow of Duct Analysis I

(b) Flow of Duct Analysis II

Fig. 7. Ventilation duct design flows for duct analyses I and II.

In this research, the Balanced-Capacity Method is used iteratively. In the first iteration, the diameters of the longest route L_{123} (D_1, D_2, and D_3) are assumed to be D. Because Q_i is known based on the relationship in Eq. (2), the air velocity in ducts 1, 2, and 3 can be determined using Eq. (3). Hence, the total pressure drop in duct 1, ΔP_1, can be calculated using Eq. (5); the total pressure drops in ducts 2 and 3 (ΔP_2 and ΔP_3) can be calculated in the same way.

The pressure drops per unit length of ducts 1, 2, and 3, i.e., dhu_1, dhu_2, and dhu_3, can then be calculated according to its definition (Eq. (4)). Thus, one can determine the new diameters for ducts 1, 2, and 3 (D_1', D_2', and D_3') from Eqs. (8)-(10). The new diameter of duct L_7 (D_7') can then be determined from Eq. (1) because Q_7 is known.

$$D_1' = \left(0.00187 \times \frac{Q_1^{0.9}}{dhu_1}\right)^{\frac{1}{5.02}} \tag{8}$$

$$D_2' = \left(0.00187 \times \frac{Q_2^{0.9}}{dhu_2}\right)^{\frac{1}{5.02}} \tag{9}$$

$$D_3' = \left(0.00187 \times \frac{Q_3^{0.9}}{dhu_3}\right)^{\frac{1}{5.02}} \tag{10}$$

Using a similar approach, one can determine the new diameters of ducts L_4 and L_5 in route L_{145}, i.e., D_4' and D_5'. Because ducts 5 and 6 are branched from the same place, the new diameter of duct L_6 (D_6') can be calculated in the same way as diameter D_7'.

Before performing another iteration, the differences between diameters D_i' and D_i obtained in two consecutive iterations should be calculated, and convergence can be concluded when the difference ratio (D_i' - D_i) of each duct is less than a pre-set error range.

2. Duct Analysis I-Uniform Ducts

The following steps are the process flow (Fig. 7(a)) of the Duct Analysis I code developed to calculate the diameters of ventilation ducts.

(1) Assume a constant for the equivalent diameter $(D_i)^0$ (mm) of each duct, and calculate the flow rate Q_i (m^3/min) of each duct based on the assigned flow rates at the outlets of the ventilation system.
(2) Calculate the air flow speed V_i (m/s) based on the flow rate and diameter of each duct segment.
(3) Calculate the total pressure ΔP at each outlet.
(4) Calculate the new equivalent diameter $(D_i)^1$ of the i-th duct using the Balanced-Capacity Method (using Eqs. (3), (5), (4), and (1) in sequence, see Section 4.1 for details).
(5) Replace the diameter $(D_i)^0$ in Step 1 with the new equivalent diameter $(D_i)^1$ obtained in Step 4. Repeat Steps 1 to 5 until the diameter difference between consecutive iterations ($(D_i)^{n+1} - (D_i)^n$) is less than 0.1 mm for each duct.

3. Duct Analysis II-Expanded Ducts

In the working plan design of the ventilation system, the New Duct Analysis II is used, which is the second application phase of the Balanced Capacity Method (Fig. 7(b)). In such an analysis, circular ducts are replaced with rectangular ducts, and the duct components such as branches and associated reducers in the ventilation system are considered.

Considering the shipbuilding practice that the lengths and widths of rectangular ducts are multiples of 50 mm, it is impractical to keep the effective area of a rectangular duct the same as that of the circular duct. Therefore, the dimensions of the rectangular ducts will be used as initial guess values in the Balanced-Capacity Method to go through iterations until the convergence criterion is satisfied, i.e., the variation in cross section areas is less than a small value.

In reality, a reducer will be added after a branch along the ventilation route to convert the equivalent diameter to a smaller one. Including the influence of the dimensions of the branches and reducers on the equivalent length of the route is another aspect of New Duct Analysis II. The air quantity deliveries of both the main route and the branch routes will be checked against the design requirements in the iterations to obtain suitable sets of dimensions for the rectangular ducts. The dimensions of the ducts obtained in new Duct Analysis II are, in general, larger than the uniform rectangular ducts determined by New Duct Analysis I.

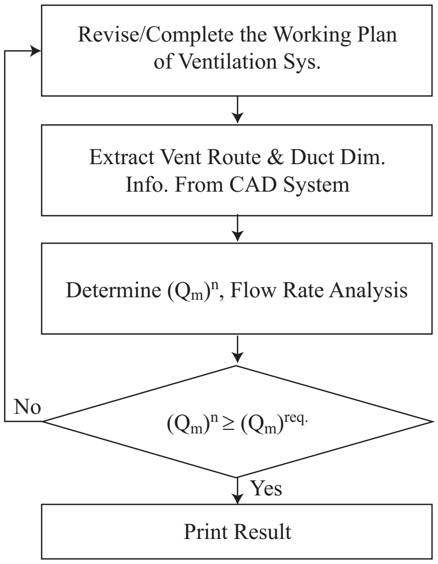


Fig. 8. Flow rate analysis after modifications of the ventilation duct routes.

The ventilation routes and duct dimensions determined in this analysis can be used to construct 3D PDMS models. The isometric projections and AutoCAD formatted top view of the ventilation system model can be generated from such models.

4. Duct Analysis II-Air Quantity Recheck

Duct Analysis II can also be used to predict the flow rates that are delivered at the outlets of a given ventilation system design, where the rectangular cross section dimensions and the routes of the system are known. Such an analysis would be needed when the routes of the ventilation system are modified in the working design after the duct expanding process (for instance, to avoid interference with structures, Fig. 7(b)).

A Visual BASIC code-VB.NET-was developed to retrieve ventilation duct information from CAD models developed in the working plan design phase for the Flow Rate Analysis, including determining pressure drops, duct dimensions, and air quantity delivery (ASHRAE, 2009a, 2009b). The detail procedure is described below (Fig. 8).

1) Step 1. Input the Diameters and Routes of the Ventilation System

During the working plan design phase, the ventilation routes could be modified to avoid interference between ducts and structural members. Hence, the revised ventilation duct information will be used.

2) Step 2. Determine Flow Rate Deliveries (using Eqs. (1), (4), and (5))

Calculate the total pressures from the draft fan (FTP) to the outlets (ETP). If the variations in the flow rates delivered at the outlets are very small, ETP is zero. The total pressures at the outlets should be identical, see Eq. (11). Next, define the dynamic pressure ΔP_{id} as $\frac{\rho V_i^2}{2}$. Because the dimensions of the ventilation ducts are given, the variations in the localized loss coefficients are not significant. To make ETP equal to zero, the dynamic pressure of each duct needs to be adjusted. When the dimensions of the ducts are given, adjusting the air quantity of the duct segment is equivalent to adjusting the velocity, and the dynamic pressure will be changed accordingly. Because the air quantity of each duct segment will be changed when the air quantities at the outlets are changed, modifying the dynamic pressures at the outlets will cause changes in the dynamic pressures of other duct segments and in the accumulated pressure drop in the route. In other words, one can adjust the air quantity in each duct segment of a ventilation duct route by adjusting the air quantities at the outlets. Return to Step 1, and revise the air quantities at the outlets until convergence is achieved.

3) Step 3. Check Whether the Design Requirements are Satisfied; Otherwise, Revise the Duct Dimensions

If the differences between the required and calculated air deliveries at the outlets are very small, stop the calculation. Otherwise, if the calculated air quantity deliveries are smaller than required, a larger duct size will be used (and if larger, a smaller duct size will be used). Return to Step 1 to redo the design calculation.

$$\frac{FTP - ETP}{FTP} \approx \left(\frac{Old\ Flow\ Rate}{New\ Flow\ Rate}\right)^2 \approx \frac{Old\ Dyna.\ Press.\ at\ Outlet}{New\ Dyna.\ Press.\ at\ Outlet} \quad (11)$$

Table 2. The characteristics of the main engine of the ship.

Item	Characteristic
Engine type	MAN B & W 7K98MC6 Marine Diesel Engine
Power	Maximum continuous output 54460 PS
No. of cylinders	7
Bore cylinder	980 mm
Action type	2 strokes

Table 3. Average Errors of the Ventilation Outlets.

Fans	Total number of outlets	Average Error
No. 1 Fan	25	22.488%
No. 2 Fan	24	17.882%
No. 3 Fan	21	25.143%
No. 4 Fan	22	20.080%
Average (over the 4 fans)	21.398%	

V. ONBOARD TEST AND COMPARISON

The new ventilation system design process has been applied in the design of the engine room ventilation systems of a 4,662 TEU container ship. The characteristics of the main engine of the ship are presented in Table 2. The air quantity deliveries at the outlets of 4 ventilation systems were predicted using Flow Rate Analysis at the end of the working plan design phase, and the air quantities actually delivered by the 4 constructed ventilation systems were measured during the sea trial.

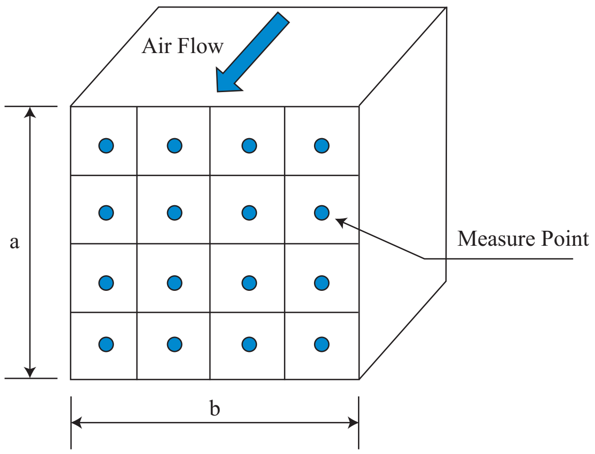


Fig. 9. The air flow velocity and cross section area.

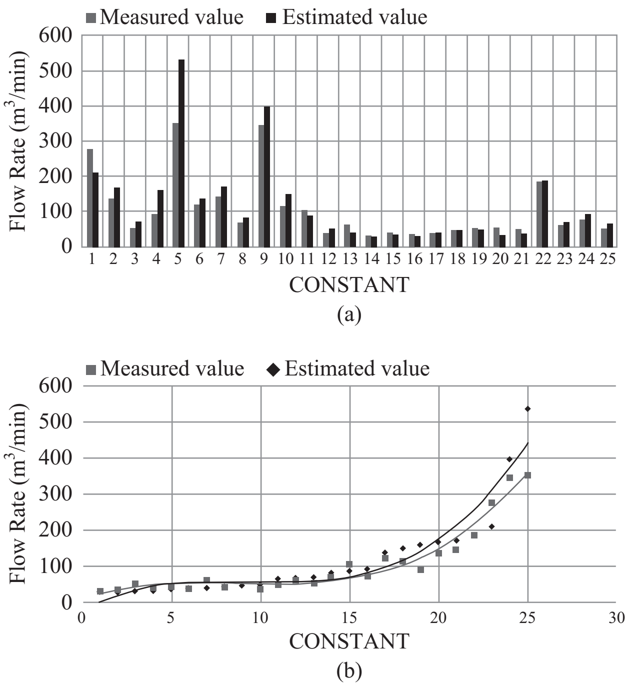


Fig. 10. Flow rates at the outlets of the No. 1 fan (a) and the NCC (b).

During the trial, the main engine was running at Nominal Maximum Continuous Revolution (85% of MCR). The measurements were taken at the entrances of the forced draft fans and the outlets of the ventilation systems. The 16 subdivisions of the outlet sections and the measuring positions and orientations were according to the Chinese National Standards 2726 and 7779 (CNS, 1973, 1981). The air flow velocity is the average of the measured velocities at the 16 subdivisions. The "measured" air quantity delivery at the outlets was actually calculated from the air flow velocity and cross sectional area, Fig. 9. The air quantity deliveries to be compared are those predicted by the Flow Rate Analysis based on the ventilation system models selected in the working plan design phase.

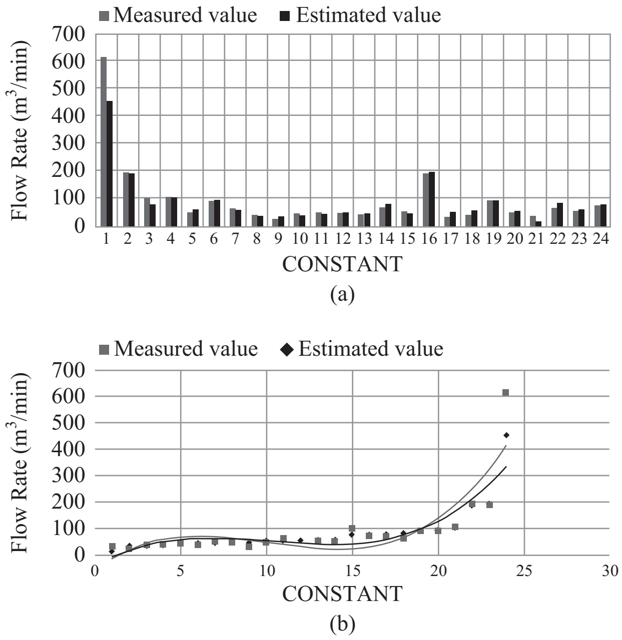


Fig. 11. Flow rates at the outlets of the No. 2 fan (a) and the NCC (b).

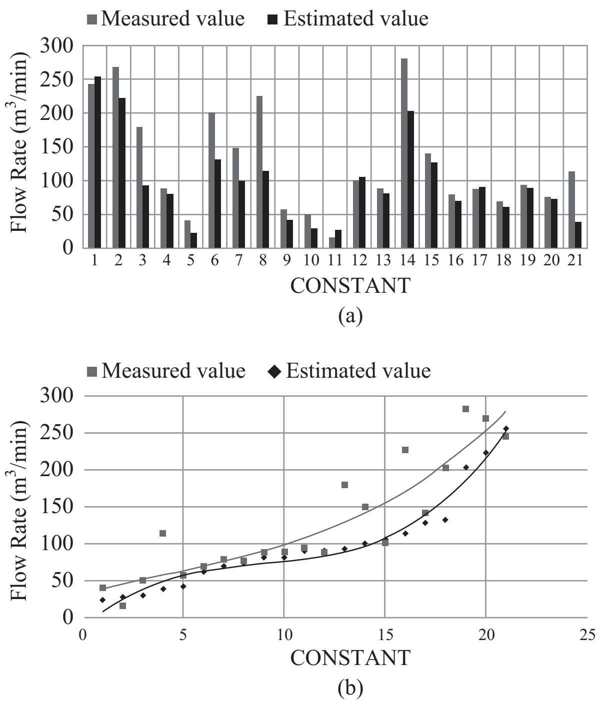


Fig. 12. Flow rates at the outlets of the No. 3 fan (a) and the NCC (b).

Figs. 10-13 illustrate the air quantities measured and predicted for the outlets of the four ventilation systems/fans. Table 4 shows the air quantities measured and designed for the outlets of the four ventilation systems/fans. The error between the design and measured values is shown in Table 4 and summarized in Table 3. Table 3 lists the average errors of individual ventilation fans (the difference percentage of the sum of the

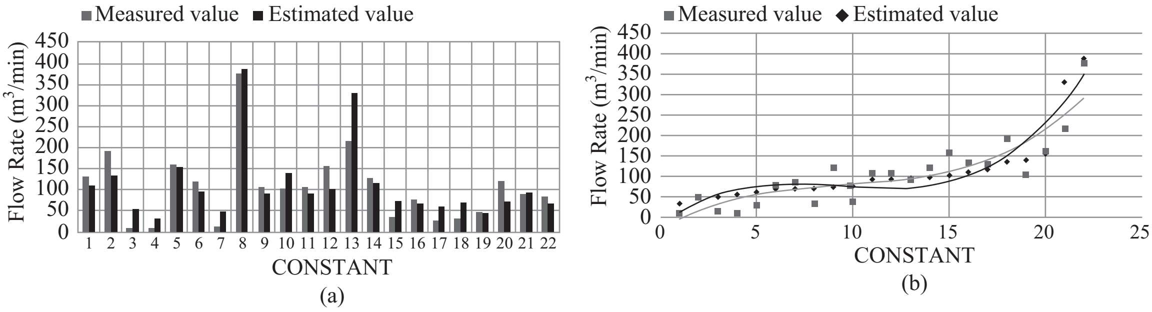


Fig. 13. Flow rates at the outlets of the No. 4 fan (a) and the NCC (b).

Table 4 (a). No. 1 fan measure and design values.

Section	Air Flow (m^3/min) (Measure)	Air Flow (m^3/min) (Design)	Velocity	Error
22	277.526669	210.9637016	14.95	23.98435
50	137.185287	169.0787912	11.15	23.24849
51	54.498926	70.77394096	8.411111	29.863
25	92.5528285	161.0766086	9.142857	74.03748
45	354.490885	535.4214719	9.265	51.03956
44	122.62256	139.5735179	10.92778	13.82369
47	146.551292	173.400023	10.41429	18.32036
48	69.0182713	82.84938083	8.768421	20.03978
3	346.100817	397.932308	18.644	14.97584
49	115.8825	150.265385	10.16818	29.67047
2nd DK	1716.43003	2091.335129		
31	107.992924	88.76585083	15.036	17.80401
33	39.6419087	53.02605725	7.828	33.76262
30	61.8040753	41.14829133	9.969231	33.42139
13	33.1219383	30.39712128	7.860714	8.226623
15	40.979987	33.41312212	8.669231	18.46478
17	37.0811714	30.62507579	7.844444	17.41071
18	39.6542388	40.87935539	7.830435	3.089497
11	46.832955	46.54064306	9.248	0.624159
16	52.3254457	49.02702419	7.7875	6.303666
14	53.3952259	32.85199747	9.882143	38.4739
12	49.2892203	37.65137295	9.122222	23.61134
36	187.354861	188.1667332	8.968	0.433334
3rd DK	749.473951	726.7290046		
38	61.0850958	69.47018118	7.352174	13.72689
41	76.0347145	92.44669912	6.776	21.58486
40	52.0361486	65.70774609	7.744444	26.27327
M-floor	189.155959	227.6246264		
Qt-1	2655	3045.68876		22.48856

Table 4 (b). No. 2 fan measure and design values.

Section	Air Flow (m^3/min) (Measure)	Air Flow (m^3/min) (Design)	Velocity	Error
2	614.8910847	453.875857	18.21034	26.18598
23	193.4489306	188.557026	8.817391	2.528783
43	103.0945897	77.7873632	9.1875	24.54758
30	106.7035347	103.92	7.582609	2.608663
34	48.79610723	59.4966971	5.873077	21.92919
26	90.62908986	93.5212811	6.778261	3.191239
41	63.25366072	55.6978679	7.022727	11.94523
40	39.6616472	35.9850117	7.145	9.270002
39	24.81811771	34.519507	4.204762	39.08995
38	43.50899483	37.3840909	7.838095	14.07733
53	47.20483547	43.1567983	5.240909	8.575471
29	46.30067018	48.8168528	5.572727	5.434441
33	39.46509	45.8254077	4.75	16.11631
52	67.08909967	79.7602363	6.865217	18.88703
	52.57903263	46.4437874	7.626087	11.66862
2nd DK	1528.865453	1358.304		
21	190.2224924	195.002847	9.105263	2.513033
20	32.7307251	49.4366393	4.557143	51.04046
19	39.44014456	56.3194527	5.491304	42.79728
22	90.85315444	93.1711562	10.08696	2.551372
17	48.44385158	53.3822617	6.154545	10.19409
16	34.87954565	14.4872519	5.36	58.46491
3rd DK	436.5699137	461.799609		
11	64.15053611	83.7853994	8.15	30.60748
12	53.28481447	57.7217247	6.769565	8.326782
13	73.52313204	78.3903223	9.340741	6.619944
M-Floor	190.9584826	219.897446		
Qt-2	2156.393849	2040.00105		17.88213

Table 4 (c). No. 3 fan measure and design values.

Section	Air Flow (m^3/min) (Measure)	Air Flow (m^3/min) (Design)	Velocity	Error
2	243.8389	254.307308	17.32778	4.293156
22	268.3774	221.829371	14.45714	17.34425
26	179.4326	92.5160405	13.285	48.43968
25	88.76893	81.1337902	9.855556	8.601137
27	41.4008	23.643085	9.442857	42.8922
18	201.1063	131.801315	13.3	34.46187
19	148.9164	98.8992737	10.58235	33.58737

Section	Air Flow (m^3/min) (Measure)	Air Flow (m^3/min) (Design)	Velocity	Error
17	225.6935	113.615929	11.46111	49.65919
20	57.67467	42.4849424	11.38889	26.33691
21	50.46244	29.3215094	9.964706	41.89439
	15.77252	27.1568794	4.483333	72.1784
2nd DK	1505.672	1089.55256		
35	101.0374	105.562876	9.004167	4.479038
36	88.35459	80.9712685	7.873913	8.356471
33	280.4534	202.138845	13.84091	27.92428
37	140.9278	127.44406	12.55909	9.567847
31	79.13603	69.4575602	7.052381	12.23017
30	88.35324	89.7099631	8.728	1.535562
32	69.20427	61.6921635	6.836364	10.85498
3rd DK	847.4668	736.976736		
12	93.2028	89.4616776	10.34783	4.013964
38	75.94533	73.1516586	8.431818	3.678534
39	113.8406	39.0570197	12.63913	65.69148
M-Floor	282.9887	201.670356		
Qt-3	2636.127	2028.19966		25.14385

Table 4 (d). No. 4 fan measure and design values.

Section	Air Flow (m^3/min) (Measure)	Air Flow (m^3/min) (Design)	Velocity	Error
6	131.99	109.0372897	14.65417	17.38973
5	191.286	134.3860604	21.2375	29.74601
	323.276	243.4233502		
3	8.985648	54.33428261	2.554167	504.6785
42	9.485474	31.08584874	3.857143	227.7206
10	160.2017	154.0313493	17.78636	3.851594
43	121.5043	97.29344595	13.49	19.92595
41	13.05191	48.23868823	3.71	269.591
13	375.6649	386.863982	11.93158	2.981143
15	107.1327	91.57145924	9.547368	14.52523
	103.3553	138.9377115	11.475	34.42733
2nd DK	899.3819	1002.356768		
35	106.9987	90.51723009	6.916667	15.40344
36	156.6658	101.6568423	10.12727	35.1123
37	216.6629	329.9609627	6.881481	52.2923
30	127.3536	116.146631	7.558621	8.79985
31	36.12556	73.41789295	4.803333	103.2298
27	76.75824	67.59595021	6.35	11.93655

Section	Air Flow (m^3/min) (Measure)	Air Flow (m^3/min) (Design)	Velocity	Error
45	27.66948	59.5340488	3.072	115.1614
33	33.03765	69.53416026	3.668	110.4694
28	48.46455	45.80916033	5.380769	5.479045
3rd DK	829.7365	954.1728787		
39	120.3236	73.06082509	12.232	39.27972
40	90.62141	93.43323775	9.2125	3.102831
20	84.66125	68.66969349	11.7875	18.88888
M-Floor	295.6063	235.1637563		
Qt-4	2348.001	2435.116753		20.08036

Table 5. Comparison of existing and new ventilation systems designs.

Project design method	Design and recheck (day)	Description
Existing ventilation system design	45 (design) + 3 (sea trail)	1. 2D Draft-Key plan diagram for ventilation arrangement. 2. Diameters & air flow quantity. 3. Data & database (partial 3D model for working design). 4. Round vent path. 5. Measure.
New ventilation system design	20 (design) + 1 (program)	1. 3D Plan-Key plan diagram for ventilation arrangement. 2. Diameters & air flow quantity. 3. Database (full 3D environments for working design). 4. Uniform vent path & expansions vent path. 5. Predict.

measured air quantity deliveries from the sum of the predicted values). The average error over the 4 fans is 21.398%, which means the measured air quantity deliveries are 21.398% higher than the predicted ones. One of the reasons for such a result is that the surface roughness of the ventilation ducts in the computer prediction code was set to be 1-2 year usage due to dust attachment on the duct surfaces, but the test was conducted on the newly constructed ship.

The second factor, which can burry measurement errors in the air deliveries at the 16 regions of an outlet, is that the air velocities were sampled sequentially instead of simultaneously.

Even with an over-prediction of 21.398%, the average normalized cross-correlation (NCC) (Sun et al., 2006), Eq. (12), of the four ventilation systems is 93%, which indicates the high reliability of the analysis method/codes.

$$NCC = \frac{\sum_x \sum_y (A_{xy} - \overline{A})\left(B_{xy} - \overline{B}\right)}{\left[\sum_x \sum_y (A_{xy} - \overline{A})^2 \sum_x \sum_y \left(B_{xy} - \overline{B}\right)^2\right]^{1/2}} \qquad (12)$$

where A_{xy} is the estimated value, B_{xy} is the actual measured value, and A and B are the means of each parameter. Finally, both the measurements and analyses conducted in this research showed that for the same supply fan, the differences in the air quantity deliveries at the outlets on the lower deck (a relative high pressure region) are smaller than those on the higher decks (low pressure region).

VI. CONCLUSION AND DISCUSSION

First, this research developed a new ventilation system design process using the PDMS CAD system as a modeling tool and the Balanced-Capacity Method as an analysis tool. This process improves the ventilation system design to a fully 3D method, which is shown in Table 5.

Second, the process requests and allows design engineers to predict the air quantity deliveries at the outlets of the ventilation system and to check whether the design requirements are satisfied in the working plan design phase.

Third, the predicted air quantity deliveries of a 4662 TEU container ship were compared with the air quantity deliveries measured during the sea trial. Although the average error between the sum of the measured air quantity deliveries and that of the predicted ones is 21.4%, the NCC values indicate high reliability of the prediction/analysis code.

The advantages of using the new design process include (1) the variations in the ventilation routes and duct dimensions in the key plan design phase and the working plan design phase are small. (2) Engineers are provided with the freedom to change the ventilation system design and can predict the air quantity deliveries of the new design.

In the future, the design environment may also be considered in the overall design of duct system in the engine room, including the cable and piping arrangements.

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