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Periodic Modulation and Functional Demonstrations of Mechanically Operated Reciprocating Ventilator

Siddhant R. Motghare[1], Dr. P. G. Mehar[2], Er. V. D. Dhopte[3], Dr. S. R. Ikhar[4]
[1]*Scholar, Dept. of Mech. Engg., K.D.K. College of Engg., Nagpur - 09*
[2, 3]*Asst. Professor, Dept. of Mech. Engg., K.D.K. College of Engg., Nagpur - 09*
[4]*Asso. Professor, Dept. of Mech. Engg., K.D.K. College of Engg., Nagpur - 09*

Abstract: During this period of COVID-19 pandemic, the lack of medical equipment (like ventilators) leads to complications arising in the medical field. A low-cost ventilator seems to be an alternative substitute to fill the lacking. This paper presents a numerical analysis for predicting the delivered parameters of a low-cost mechanical ventilator. Based on several manufactured mechanical ventilators, two proposed designs are investigated in this study. Fluid-structure interaction (FSI) analysis is used for solving any problems with the first design, and computational fluid dynamic (CFD) analysis with moving boundary is used for solving any issues with the second design. For this purpose, ANSYS Workbench platform is used to solve the set of equations. The results showed that the Ambu-bag-based mechanical ventilator exhibited difficulties in controlling ventilation variables, which certainly will cause serious health problems such as barotrauma. The mechanical ventilator based on piston-cylinder is more satisfactory with regards to delivered parameters to the patient. The ways to obtain pressure control mode (PCM) and volume control mode (VCM) are identified. Finally, the ventilator output is highly affected by inlet flow, length of the cylinder, and piston diameter.
Keywords: Mechanical ventilator, Fluid-structure interaction, CFD, COVID-19

I. INTRODUCTION

COVID-19 outbreak has become a global issue as this new pandemic has strongly affected the world. This virus causes a substantial global health problem with very significant economic and social impacts. Studies have shown that most people affected by COVID-19 have mild symptoms, but other people, like adults over 65 and those with chronic illnesses, develop severe symptoms in the pulmonary system. This is reflected by the fact that the potentiality of these groups of people to exchange carbon dioxide and oxygen between blood and lungs begins to fall once they are attacked by the virus. At this stage, patients are hospitalized to support their lung functions with mechanical ventilation, as it is the best medical treatment currently recommended by doctors. It has been reported that the early use of endotracheal intubation (invasive intubation) can cause secondary lung infection because of the risk of germs entering through the tube, which carries air and oxygen to the patient. So, non-invasive ventilation could be an excellent choice to avoid the multiplication of lung damage induced by mechanical ventilation.

Faced with the large influx of patients, hospitals do not have enough respirators to meet their needs. The medical equipment industry offers various highly sophisticated devices in the market, but that available number still cannot meet the demand of hospitals. Thus, several enthusiastic research teams have used their competence to develop a simple design and low-cost respirators manufactured in a large number within a short period. Among many low-cost ventilators, a published MIT student project using Ambu-bag, which is available freely online, is referred. However, a respirator is not just a pump that forces air and oxygen into the patient's lung. One of the critical problems encountered by doctors during mechanical ventilation is Barotrauma. Indeed, when there is difficulty adapting between the pressure delivered by the ventilator and that inside the lungs, an alveolar overdistention can occur, further causing barotrauma.

In the respiratory system (Fig. 1), breathing is controlled by the diaphragm, which is a muscle separating the abdomen from the chest, and the intercostal muscles, which are located between the bones of the rib cage. During inspiration, the diaphragm contracts and moves toward the abdomen cavity, and the intercostal muscles contract to lift the rib cage outward. As a result of these two muscle movements, the volume of the rib cage increases, and the pressure in the cavity where the lungs are housed, decreases.

The increase in volume and the decrease in pressure urge outside air to fill the lungs, to balance the pressure in the lungs with external atmospheric pressure. During the expiration phase, the process is reversed, where the pressure inside the lungs increases above atmospheric pressure, thus resulted in a pressure difference which draws air out of the lungs

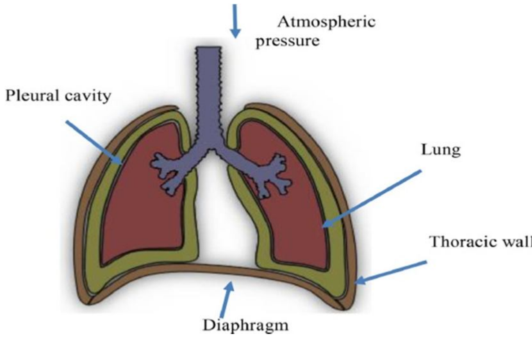

Fig. 1: The physiology of the breathing system

Mechanical ventilation works entirely differently than the physiological breathing system. Instead of having depression during the inspiration, the mechanical ventilators push the gas by creating high position pressure. The ventilatory parameters are carefully adjusted by the doctor according to the ventilation mode that has been chosen. It is possible to change the inspired oxygen fraction between 21% and 100% while maintaining positive expiratory pressure (PEEP) in the circuit during expiration.

A mechanical ventilator, inhalation circuit, exhalation circuit, and an artificial lung are required to simulate the complete breathing process. Several pieces of research were conducted to experimentally and theoretically study the ventilation parameters. It is important to note that the inspiration stage is related to the ventilator.

Based on this review, there are no numerical simulations on flow produced by mechanical ventilators. This type of simulation is essential to evaluate the performance of the design before proceeding to the fabrication stage. The study of the mechanical ventilation process requires the use of fluid-structure interaction (FSI). The FSI problems play prominent roles in many scientific and engineering fields, yet a comprehensive study of such problems remains a challenge due to their strong nonlinearity and multidisciplinary nature FSI method couples computational fluid dynamics used for fluid flow with finite element analysis used for the solid domain. It enables the investigation of the fluid behavior, structural behavior, and how they interact and affect each other. In a One-Way FSI study, the results obtained from the solution fluid or structural domain are used as a boundary condition when solving the different domain. In a Two-Way FSI study, at each sub-step, the fluid and structural domain solutions are solved in parallel. The solution must be converged before moving to the next step

II. MECHANICAL VENTILATION PROCESS

The operating principle scheme of mechanical ventilation is illustrated in Fig. 2 . Frequently, the respiratory cycle consists of the inspiratory time (TI) of 1 s and the expiratory time (TE) of 2 s. In this case, the respiratory frequency is often 20 cycles per minute. Once inspiration gets triggered, the insulator opens the inspiratory valve VA (Fig. 2) and closes the expiration valve VB, causing the airway pressure to rise and then, compressed gas enters the lung. During expiration, the mechanism is reversed. The inspiratory valve is closed and the expiratory valve opens, causing the airway pressure to drop, and the gas leaves the lung (passive exhalation). These two valves always act in opposite ways. However, this mechanism cannot generate a PEEP. The regulation of the expiratory valve causes the desired PEEP by taking into account the resistance of the breathing circuit.

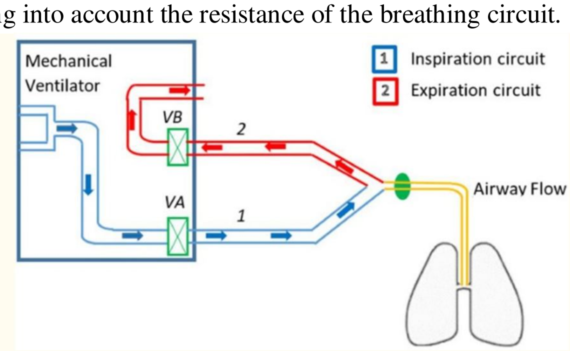

Fig. 2 : The operating principle scheme of mechanical ventilation

There are two basic modes for mechanical ventilation according to variables that are controlled during inspiration. These include volume-controlled mode (VCM), which is commonly used, and pressure-controlled method (PCM) ventilations. In PCM, the value of the maximum pressure is adjusted. However, the current volume and flow delivered to the patient depended on the importance of the inspiratory pressure and the set PEEP level. In the VCM, the volume and the flow remain constant. Simultaneously, the pressures vary from one patient to another depending on the compliance and resistance of the respiratory system and the patient's inspiratory contribution.

III. DESIGN AND MODELING OF MECHANICAL VENTILATORS

As previously mentioned, a mechanical ventilator, inhalation circuit, exhalation circuit, and an artificial lung are required to simulate the complete breathing process. Therefore, this study is focused on the simulation of the flow inside the mechanical ventilator. Two different ventilators, namely Ambu-bag and piston-cylinder-based ventilators, are considered in Sections 3.1 and 3.2. The flow rate and volume evolution as a function of time during the inspiration phase were calculated for each design (Circuit 1 in Fig. 2).

In this section, mathematical formulations and solution procedures for the two proposed designs are presented. For the Ambu-bag-based design (Section 3.1), the Fluid-structure interaction (FSI) analysis methodology is illustrated with boundary conditions, material properties, and mesh generated. However, for the piston-cylinder-based design (Section 3.2), the CFD analysis is more appropriate to evaluate the designed performance. The geometry, boundary conditions, material properties, and mesh adopted in this analysis are also presented. Therefore, flow rate and delivered volume by the ventilator are calculated. The pressure at the outlet is not calculated due to the calculation of pressure at the outlet of the mechanical ventilator requires the entire system to be simulated. In this case, the gas delivered flows to the atmospheric environment.

A. *AMBU-BAG-Based Design*

A modified version of the low-cost mechanical ventilator (Fig.3) proposed in this study was designed using the Solid works software. A one-step motor is used to deform the Ambu-bag by the displacement of the top hand. FSI analysis was conducted for this design. FSI occurs when Ambu-bag is bent, causing perturbation of gas flow, and then the gas generates a force on the solid.

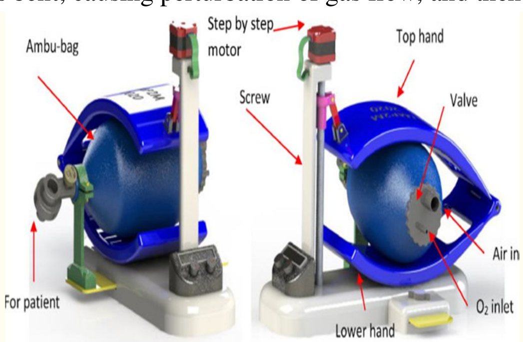

Fig. 3: Design of the Ambu-bag based on a low-cost mechanical ventilator .

B. *Piston-Cylinder Based Design*

The second design proposed in this study is shown in Fig 4 . In this design, a piston is moving in a cylinder actuated by a motor. The gas enters the cylinder from the inlet, compressed, and evacuates through the outlet.

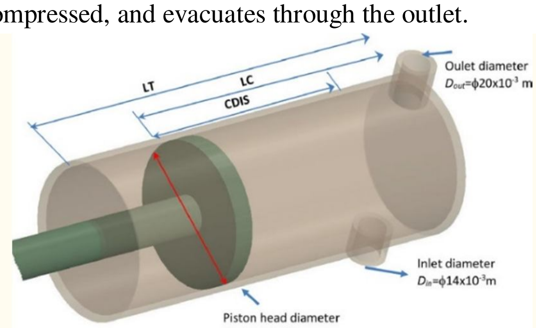

Fig. 4 : The second mechanical ventilator design.

In the first case, the piston is moved according to a uniform rectilinear motion. On the other hand, the second case follows a uniform decelerated rectilinear movement. Here, the piston velocity varies linearly from the initial velocity to the stagnation point (zero rates). The gas flow, in this case, is transient laminar. The same equations for the first design are used here. Thus, the equations of continuity, mesh displacement, and momentum are solved. The time step in CFD analysis is estimated by the Courant Number (CN) as Uref·ΔtElementSize, where Uref is the reference velocity. This parameter ensures that the fluid passes through a number of elements in one timestep. Generally, CN is taken to be a value between 2 and 10. The time step (Dt) is set to a fixed value equal to 0.01 s.

IV. RESULT & CONCLUSION

A. Results Of AMBU-BAG Based Design

Fig. 5 shows the results of the total displacement of the solid domains for different instances. The maximum removal is obtained for a time equal to 1 s at the end of the top hand. The fluid domain's mesh history is presented in Fig. 6, where each time step corresponds to a new mesh. The value of the orthogonality angle controls the quality of the mesh. During calculation over time, the solver stops when the minimum value of the orthogonality angle is below 0.2618 rad (15°) (written in Python language as minVal (Orthogonality Angle Minimum)@Default Domain < 15 [deg]). Then, the re-meshing starts, and a new mesh is transferred to CFX. The run continues until the end of the cycle.

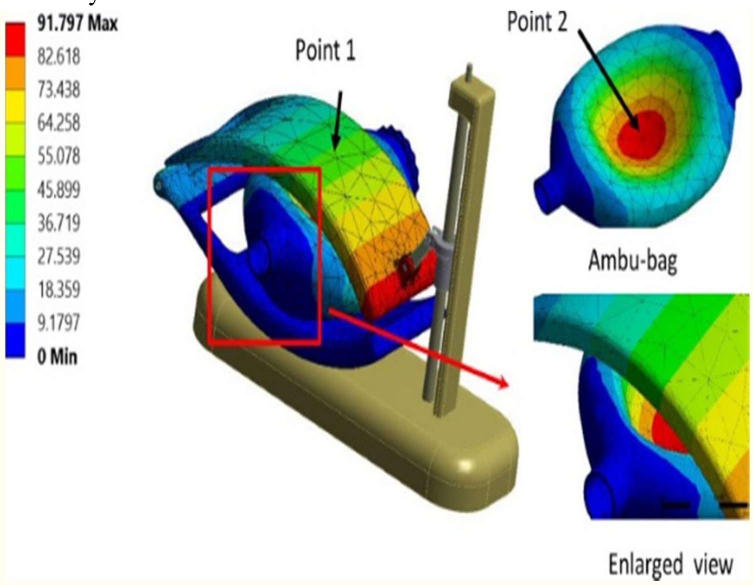

Fig. 5: Total displacement of the ventilator with silicon-rubber Ambu-bag, at 1 s. (PVC material, 100% O2, inlet flow = 12 l/min, UAZ = 0.09 m).

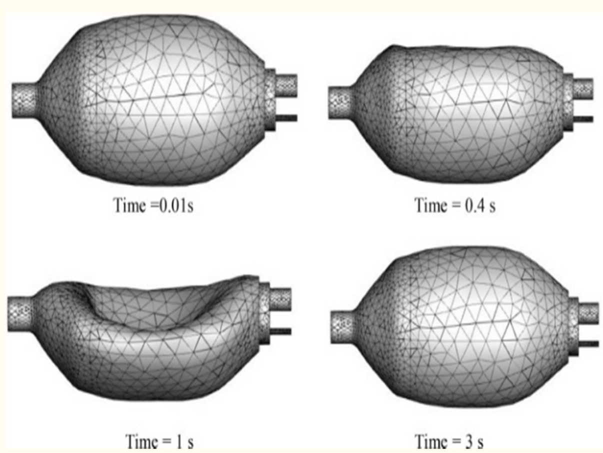

Fig. 6: Mesh history of fluid domain during one cycle of breathing. (PVC material, 100% O2, inlet flow = 12 l/min, UAZ = 0.09 m).

Results of PISTON-CYLINDER-BASED Design

The displacement of the piston wall is modeled using dynamic and deformable meshes, in which the mesh nodes are adjusted to new locations. Fig.7 illustrates the mesh displacement as the piston compressing the gas for two instances (one at the beginning and the other at the end of the piston motion). The higher values of deformation are felt near the piston wall.

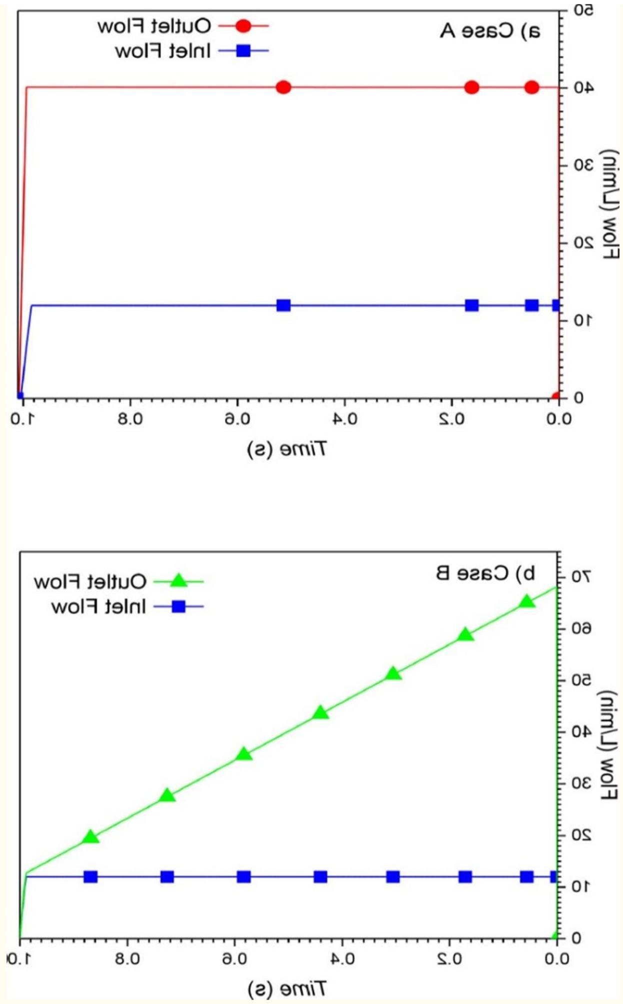

Fig. 7: Flow rate at the outlet and the inlet of Piston-cylinder ventilator for cases A and B. (100% O2, inlet flow = 12 l/min, Lc = 150 × 10−3 m, Dp = 37 × 10−3 m).

V. CONCLUSIONS

In this study, flow simulation produced by two proposed designs of low-cost mechanical ventilators was investigated. A finite element method was used to solve the set of coupled equations using ANSYS software. A transient solution during one cycle of inspiration was considered. A fluid-structure analysis was used to obtain the fluid response resulting from the Ambu-bag deformation. It was shown that the gas flow obtained is unstable. This first design (Ambu-bag-based design) is uncontrollable due to the susceptible hyper-elastic material of the Ambu-bag when force is applied. Utilization of this type of mechanical ventilators with this kind of material could lead to health problems like barotrauma. On the other hand, a CFD study with a moving boundary was performed for the piston-cylinder-based ventilator, and the results obtained were more satisfactory than the first design (Ambu-bag-based design). In this situation, two different ways of displacement of the piston were used. Two modes of ventilation (VCM and PCM modes) were evaluated. VCM was realized by a uniform rectilinear motion and PCM is realized by a uniform decelerated rectilinear motion. In addition, the effects of inflow, cylinder length, and cylinder diameter on outflow were investigated. It was found that the pattern of the outflow and the volume inspired could be controlled by manipulating these parameters. Finally, these results could be further investigated in the future by including other parameters. This requires the addition of all respiratory circuits and an artificial lung to simulate the complete breathing process

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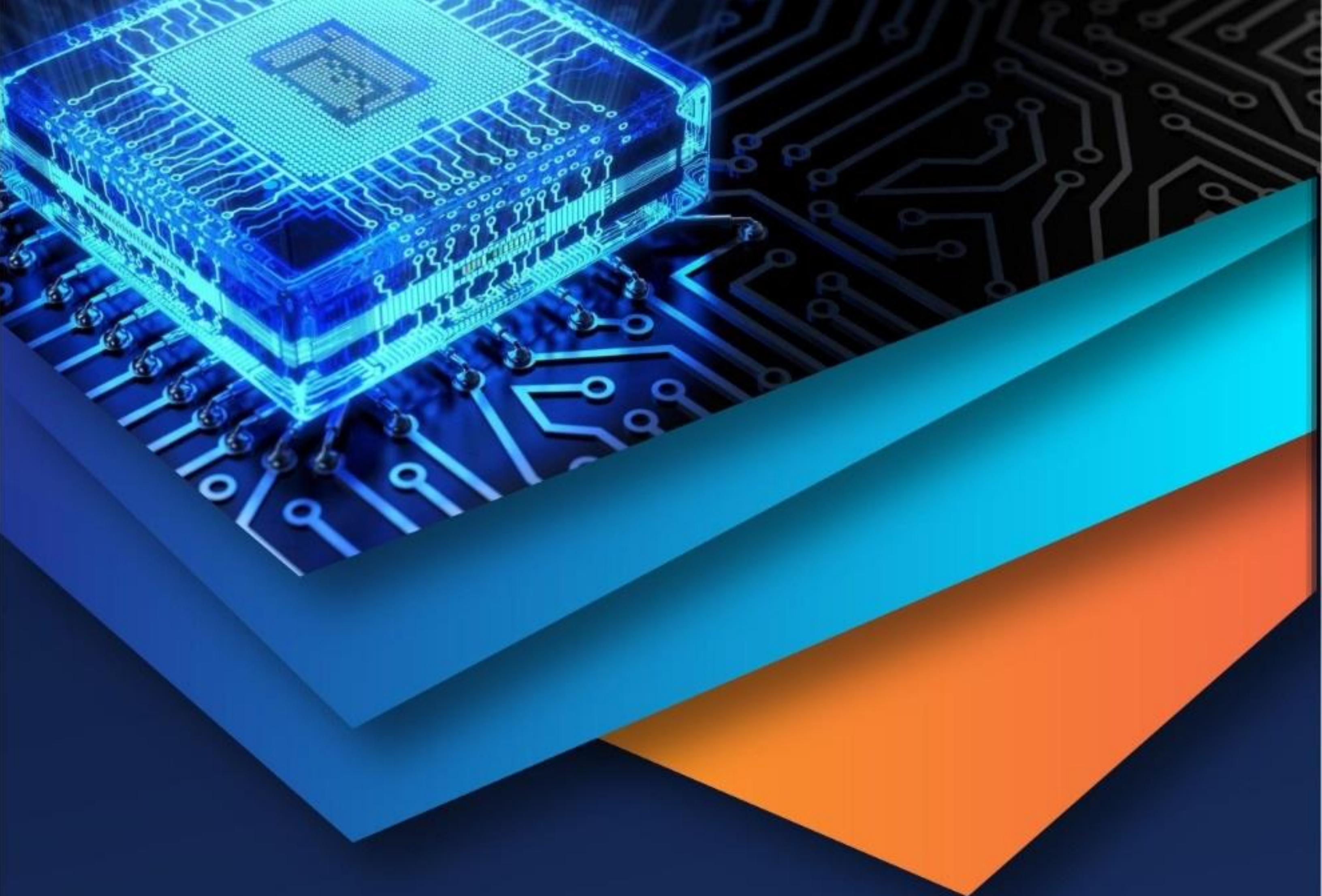

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