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Research Article

Bypass Flow Improvement in Pneumatically Driven Mechanical Blender Centric Ventilators

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ABSTRACT

Manufacturing ventilators for intended applications is always an exacting task as the requirements keep changing. The pneumatically driven ventilators have an internal blender which requires minimum pressure to operate. The balancing mechanism, bypass flow paths do not support high flow demands for extreme patient conditions. In order to address this issue, improvements in the concept of mechanical blending has been made to reduce the usage of electronics. During the tough times of COVID-19, the ventilators manufactured in large numbers should meet all extreme cases. The power consumption needs to be minimum and patient demands during portable conditions have to be met. So, the challenges faced to maintain the pressure of blended gases in the ventilator system and also incorporation of external bypass valve are discussed in this paper.

Keywords: Ventilator, Air-oxygen blender, Bypass valve, COVID-19, Hypoventilation

INTRODUCTION

Generally, all ventilators using mechanical Air-Oxygen blenders employ a mechanism which allows to activate bypass when pressure difference of inlet gases is more than 20 ± 2 psi. The primary outlet will be in the range of 2 to 120 Liters per Minute (LPM). Some blenders can deliver accurate FiO_2 (Fraction of Inspired Oxygen) even without any bleed. Minimum Bleed is required in some systems to initiate movement of springs in the check valve and also at various stages. Mechanical blenders are extensively used for oxygen therapy and also in high pressure ventilation system to provide required FiO_2 for the patient in pulsed mode operation even. Mechanical Blenders are independent of electronics like most of the gas blenders which use multiple valves and sensors. The other controlling and alarming features can be provided in the ventilator unit which has oxygen sensor at the patient end along with pressure regulators and proportional valves. They prevent any chances of Hypoventilation due to inappropriate delivery of gas mixtures. Neonatal patients require flows as low as 2 to 5 LPM at high Respiration Rate (RR) for which available blenders cannot provide the required FiO_2 accuracy.

MATERIALS AND METHODS

1D SIMULATION

Problem statement

Ventilator models which rely on supply gas pressure are less affected by changes in patient lung characteristics and ventilator settings (Campbell et al.).

Non-availability or depleting amount of any gas sources can lead to large difference in input gases of the pressure. The balancing chambers of the blender can balance the pressure variations of the input if they are nearly comparable. Any difference more than 18 psi can lead to closure of check valve of single gas in balancing chamber thus causing variation. The output pressure at that time will be of the lowest pressure gas being supplied which affects the flow of the ventilator being operated at peak flow conditions.

If the blender is not capable of meeting the demands of the patient, it compromises the effectiveness of the ventilator and consequently the health of the patient. The resistance offered by the blender should be minimum to meet high tidal volume

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requirements. Unlike the continuous flow in the high flow oxygen therapy, most of the time patient needs assisted breaths. This is achieved through A/CMV-VC (Assisted or Continuous Mandatory Ventilation Volume Controlled) A/CMV-PC (Pressure Controlled) modes.

If oxygen is of higher pressure, the diaphragm will be pushed towards the medical air. The pin on the diaphragm will push the check valve ball away from the medical air allowing more flow of air and thus less of oxygen.

Simulating the specifications

A predictive engineering analytics approach has been followed to expect the results using 1D simulation of siemens amesim software. It is used to model and simulate the current blenders in market and find the short comings of the design.

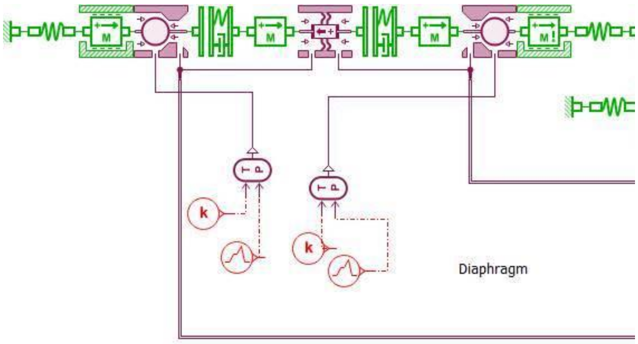


Figure 1: Diaphragm and check valves layout of blender.

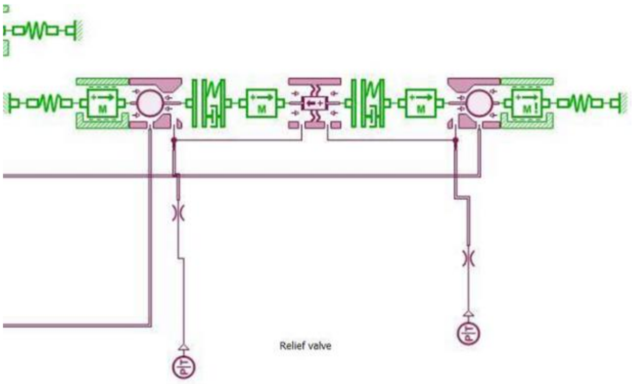


Figure 2: Simulating the condition of bypass flow.

Just after the entry through input connectors, a duckbill valve is present to prevent back flow and mixing of gases. The pressure drop observed is 5 psi at 120 LPM. The reduction in hardness will not reduce the cracking pressure so the reduction is pressure drop is not significant with the change in properties of the material. Instead an external check valve in the line can be implemented where the pressure drop ranges from 0.5 to 1 psi for the same flow.

BLOCK DIAGRAM

The blender uses a two levels of balance chambers. Around 50 psi air and oxygen gas enter through the respective inlet connectors. Each connector has a filter to trap impurities. From that, the gases go through a duckbill check valve which prevents any chance of reverse flow. After pressure equalizing in the chambers, it enters the proportioning module. As per the oxygen percentage set on control knob the proportioning module works. This module consists of a double ended needle valve positioned between two valve seats. Of the two, one seat controls the air and other controls oxygen into outlet. If knob is at the 21%, the needle valve closes flow of oxygen allowing only air to flow. And at 100% oxygen position, the vice versa happens.

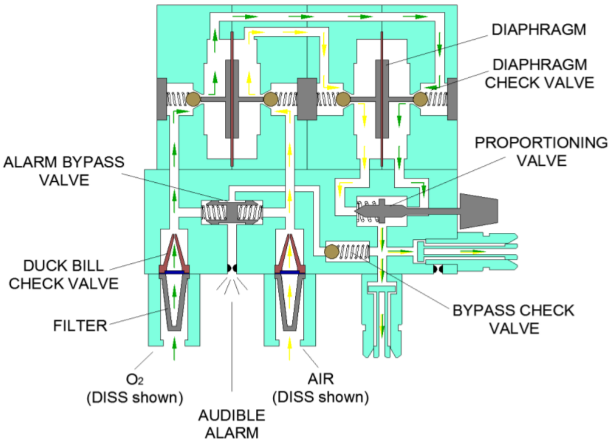


Figure 3: Block diagram of air oxygen blender.

The current system uses blender in a housing where the bleed cannot be installed on the blender. Thus a need for bleed at some other point is required to maintain accurate FiO_2 at low flows.

The pump used in the compressor system uses a reservoir of 2 Liter capacity to store the compressed air. Supporting patients for high flow demands say 200 LPM during spontaneous inhalation is the intended requirement. At 60% FiO_2 setting and 55 psi of inlet pressure, the blenders deliver 150 to 180 LPM depending on the quality of manufacturing and assembly. The output pressure measures to be 22 psi. When operated on single gas, peak flow achieved is not more than 95 LPM for an input pressure of 55 psi. For 2 Liter tidal volume set, the reservoir gets depleted of the stored gas at an instant and requires time to replete. For high RR, the response time of pump to fill the reservoir will fall short thus it calls for requirement of another storage in the ventilator system to store the mixed gas.

Shuttle and spool assembly

The spool and shuttle assembly is required to identify any differential pressure of the inlet. The shuttle is completely moved to extreme side of the spool thus allowing complete bypass flow into primary outlet area. The gas entering balancing chamber has little contribution to the flow. The shuttle resets when the difference in the pressure reaches 6 to 8 psi. The earlier designs of spool are asymmetric and give a varied pressure drop for entry of gas depending on path of gas. This is because the blenders are not designed for peak flows in bypass modes. The drop can be eliminated if the shuttle valve is made shorter to completely open the holes during extreme movement of shuttle.

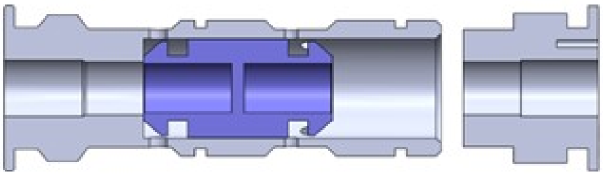


Figure 4: Shuttle inside the spool in lower block of blender.

CFD flow simulation

With flow simulation tools, the variation in pressure drops is clearly analyzed and a correction in the geometry is evaluated. With minimal changes in the overall system, the shuttle can be adjusted to new size and spool mounted in correct direction will balance the pressure drops during high flows. Air inlet in the system can be given on side of the spool opposite to extreme end to avoid any pressure drop even if the compressor outlet drops.

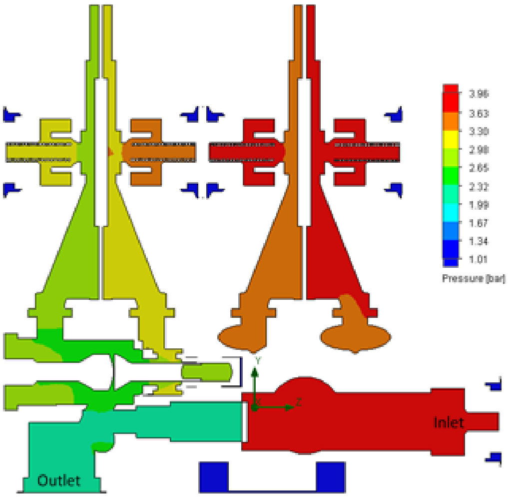


Figure 5: Pressure drop observed across inlet and outlet.

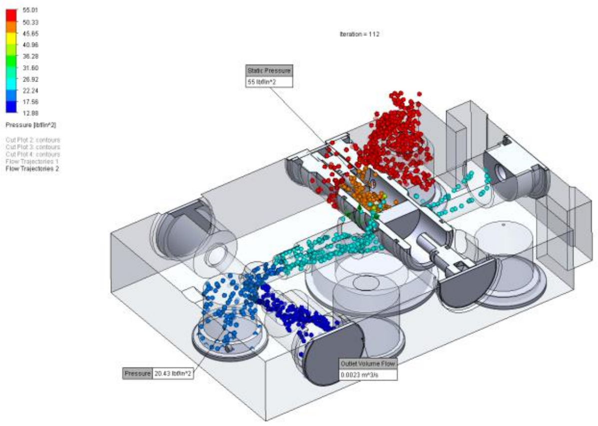


Figure 6: Original geometry with single gas operation.

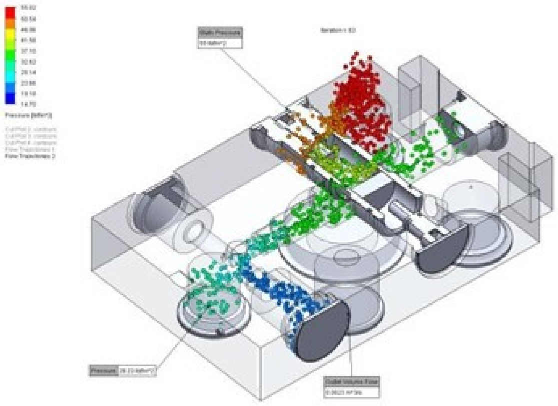


Figure 7: Modified geometry with single gas operation.

With the change in length of the shuttle, partial closing of holes in the spool can be avoided. But with a trade-off of FiO_2 variation or bypass initiation when the differential pressure is 17 ± 2.

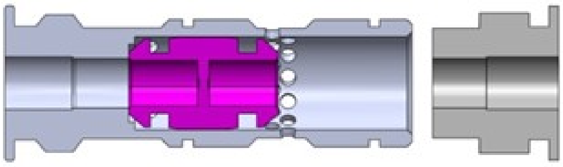


Figure 8: Block diagram of air oxygen blender.

Bypass check valve

The bypass check valve prevents the primary flow into the alarm bypass region. When the pressure at high pressure regulator drops below 20 psi, the ventilators gives a visual alarm on the display. This provides leverage to disable alarm in blender for current design. The same alarm orifice can be used to provide a bleed of 7 to 10 LPM if the bypass check valve is removed. But the problem would be to troubleshoot or identify leakages in the blender while testing. The spring stiffness is what creates resistance after exit of flow from spool. The spring stiffness is required barely to hold the backward flow of primary mixed outlet. Thus the spring stiffness is reduced 4 times. The stiffness reduction doesn't affect the leakage test as the cracking pressure of bypass is greater than the leakage gas pressure at spool O-ring.

The ball valve which has sliding ball mechanism will simulate an orifice with variable opening area. The opening area when it is closed will be the leakage area and fully open will be the maximum possible opening area. A-opening area, rB-ball radius, θ-angle between conical surface and centerline, h-valve lift. It is observed both pressure drop and flow improved with the above mentioned changes.

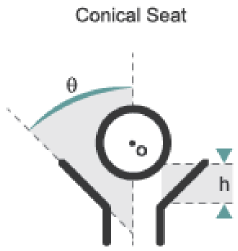


Figure 9: Ball arrangement in the conical section of the bypass.

Obserations

Table 1: Shows a/cmv mode setup in ventilator.

Ventilator Setting	
RR	15 BPM
Set tidal volume	2 L
I:E ratio	01:03
Air source	Compressor
Oxygen source	Central pipeline

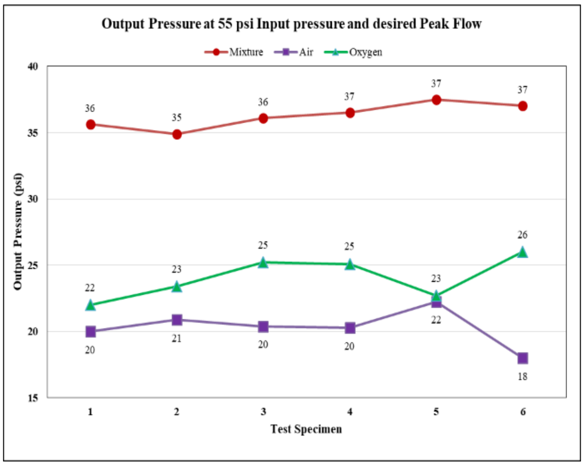


Figure 10: Output pressures of the mixture in various blenders.

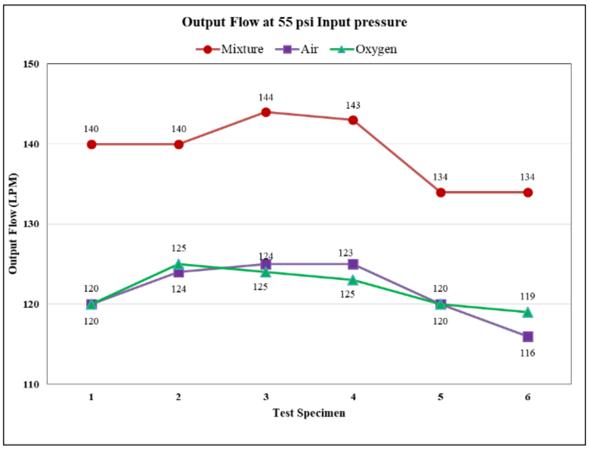


Figure 11: Output flows of the mixture in various blenders.

Improvements observed are tabulated as follows

Table 2: pressure drop and volume flow improvement.

Modification	**Pressure (psi)**	**Flow (LPM)**
Spool and shuttle	8	14
Duckbill replacement with in-line check valve	5	13
Reservoir of 800 ML capacity	2	15

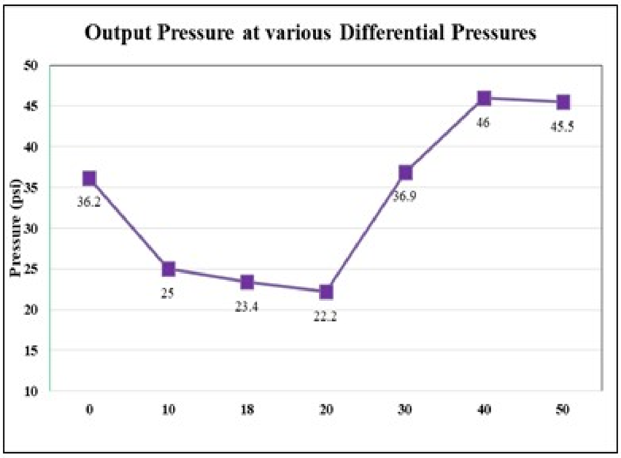
External shuttle valve assembly

External shuttle valve assembly connected in parallel to the blender, bypasses the flow directly to the reservoir whenever the differential pressure is 20 ± 2 psi. This external geometry replicates the bypass mode present in the blender inherently. The flow doesn't happen through filter, duckbill and unsymmetrical geometry like the original path and also has larger orifice opening. This provides an advantage by giving very less pressure drop. As the outlet is fed only to the reservoir, there is no need of non-return check valves. Also this assembly resets at a pressure of 8 ± 2 psi.

The shuttle in normal operation is held by the pressure on both sides until the differential pressure is created.

RESULTS

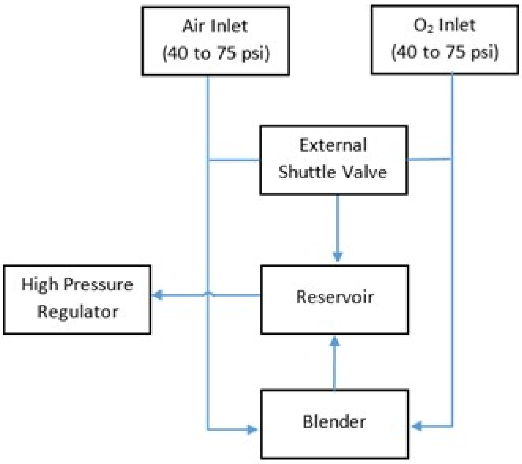
Figure 12: Output Pressure at different inlet pressures.



Implementation in ventilator system

With the above evaluations, the improved system with reservoir, external bypass valve is installed on CV200 ventilator model. The verification and validation results have been captured and the model performed well for both adult and pediatric patients with optional external bleed.

Figure 13: Block Diagram of air oxygen blender.



The system is now capable to deliver demanded flow of around 2.0 L to patient across the input range of inlet pressures. The alarming system is enabled if the pressure at the high pressure regulator is less than 20 psi for any of the failure case.

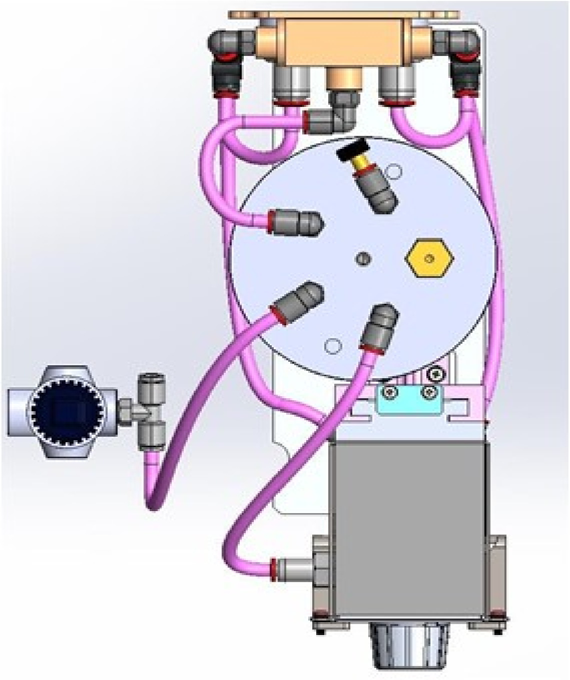


Figure 14: Layout of blender, reservoir and bypass valve.

CONCLUSION

Most ventilators use solenoid valves to control instantaneous flow output which uses additional electricity. Mechanical blender centric ventilators consume less power thus longevity of batteries increases. Turbine driven and electronic blenders have the risk of failure and frequent maintenance issues. A built-in redundancy is required to cater failure of gas supplies to the system. Thus it requires mechanism to improve flow even when operating the ventilator on single gas. With the external shuttle valve assembly and additional reservoir, the pressure drops usually observed during peak flows is completely eliminated. The external bypass also provides provision to operate when only single gas is supplied. Typical portable ventilators contain Y-cable to address single gas issues. However, if it is redirected through blender, the pressure of gas supplied won't be sufficient to supply peak outputs. Ventilators in market consume 150 to 250 W power, but with pneumatically driven systems the losses are minimized and the power consumption is only about 60 W.

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