A Study of Inhaled Pharmaceutical Aerosol (IPA) Flow Characteristic with Various Types of Fan Design in Metered Dose Inhaler

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Abstract- **Metered Dose Inhalers (MDI) is used to prevent and relieve the symptoms and progression of certain diseases (asthma, chronic obstructive pulmonary disease, cystic fibrosis and bronchiectasis) by delivering the inhaled pharmaceutical aerosols (IPA) to the desired area. The MDI is easily can be placed in a pocket or purse and ready to be used instantly and these are the reasons why it is used widely. The spacer is used to avoid deposition of most IPA on the mouth throat area whereby it promotes the expansion and mixing of the IPA before it is inhaled. However, the IPA inhaling efficiency using MDI is relatively low compared to other methods. A study on the effect of various types of fan design will carry out to understand their effects on the IPA fluid dynamics characteristics. The Computational Fluid Dynamics (CFD) software was used to analyze the IPA flow pattern inside the spacer. The expected results should show that the effective fan design will generate expected characteristics of air flow inside the spacer and will give a better delivery of the IPA through MDI spacer.**

***Keywords*-Metered Dose Inhaler (MDI), Inhaled Pharmaceutical Aerosols (IPA), Computational Fluid Dynamic (CFD), Engineering Fluid Dynamics (EFD), Hub Tip Ratio, Axial Flow Fan.**

I. INTRODUCTION

Asthma is a very common chronic disease involving the respiratory system in which the airways constrict, become inflamed, and are lined with excessive amounts of mucus, often in response to one or more triggers. These episodes may be triggered by such things as exposure to an environmental stimulant such as an allergen, environmental tobacco smoke, cold or warm air, perfume, pet dander, moist air, exercise or exertion, or emotional stress. This airway narrowing causes symptoms such as wheezing, shortness of breath, chest tightness, and coughing. Asthma can't be cured. Even when patient feel fine, they still have the disease and it can flare up at any time. Asthma affects people of all ages, but it most often starts in childhood. More than 22 million people are known to have asthma. Nearly 6 million of these people are children [4]. But with today's knowledge and treatments, most people who have asthma are able to manage the disease. Inhale Pharmaceutical Aerosol (IPA) is one of the medicines to treat asthma disease. These medicines are the most effective long-term control medicine to relieve airway inflammation and swelling that make the airways sensitive to certain substances that are breathed in. But, like many other medicines, Inhaled Pharmaceutical Aerosol (IPA) can have side effects. One common side effect from Inhaled Pharmaceutical Aerosol (IPA) is a mouth infection called thrush. A spacer or holding chamber is used to avoid thrush. A spacer or holding chamber or called Metered Dose Inhalers (MDI). Metered Dose Inhalers (MDI) attached to your inhaler when taking medicine to keep the medicine from landing in your mouth or on the back of your throat. [4] Metered Dose Inhaler is designed in small and simple manner so that it can be easy to keep and portable. Metered Dose Inhaler (MDI) allows mixing with Inhaled Pharmaceutical Aerosol (IPA) injects and reaches to patient's mouth. However the inhaling delivery of pharmaceutical aerosol is low compared to other method. An improvement was taken by adding fan in the spacer. It would help to replace the usage of propellant from Inhale Pharmaceutical Aerosol since the propellant contained CFC that very much affects to environment.

II. METHODOLOGY

A. Design

A study regarding axial flow fan was featured from references. So that the proceeding designs came out would compatible with features as shown in Table 1.

This design started with a size diameter known as hub tip ratio. Hub tip ratio represented as ratio from diameter at hub over diameter at tip.

$$\text{Hub tip ratio} = \frac{\text{Diameter at hub}}{\text{Diameter at tip}} \times 100 \qquad (1)$$

TABLE 1
AXIAL FLOW FAN FEATURES

Casing	Short Cylindrical Housing
Hub Tip Ratio	30-50%
Blade Angle at Hub	30-50 degree
Blade Angle at Tip	10-25degree

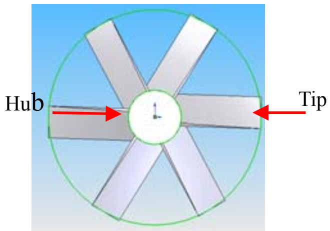

Fig. 1. Location of hub tip

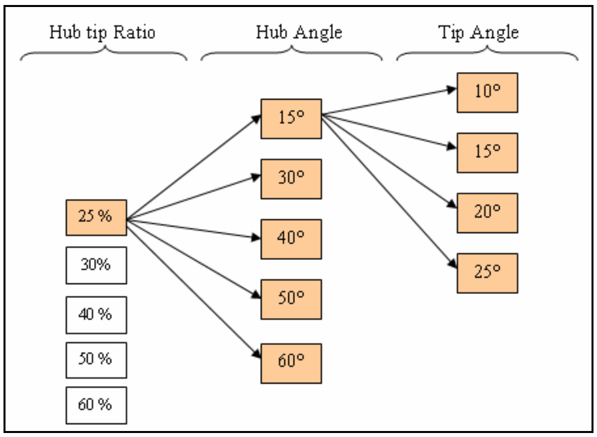

Fig. 2. Variables design

Fig. 1 shown the location of hub and tip whereby tip was located at outer blade and hub the small diameter at the center of the fan. The dimension of tip diameter remained constant as the size had to fit into spacer. Fig. 2 explained every possible parameter in axial flow fan which was hub tip ratio, hub angle and tip angle. The design had came out as shown in figure 2 as every hub tip ratio had variety hub angle and every hub angle had variety tip angle.

B. Simulation

For the first analysis, all these designs were analyzed using Engineering Fluid Dynamics (EFD) at 10000rpm to find out the best blade profile. The second analysis was by selecting best blade profile upon the previous analysis. Those designs were modified by increasing tip length more than 50%. The design was tested at 10000rpm, 15000rpm, 20000rpm, 25000rpm and 30000rpm. Since the numbers of blades remained constant (6 blades), another modification came out at 7 blades and 8 blades using the best profile by upon previous analysis in EFD at speed (10000 rpm, 15000 rpm, 20000 rpm, 25000 rpm and 30000 rpm).

III. RESULTS

A. Air Deflection and Drug Mixing in Axial Flow Fan

As the airfoil moves through air (fan blade) it normally produces positive pressures on the lower surface of the airfoil and negative pressure (suction) on the upper surface. The suction pressures on the top surface are twice as large as the positive pressures on the lower surface, but all these positive and negative pressures push and pull in approximately direction and reinforce together [1].

The streamline move in circular motion permits the drug or Inhale Pharmaceutical Aerosol (IPA) to mix with air. Let say the IPA is injected at the incoming airflow, IPA has a near density to air allow it to move along the air. Therefore aerosol will be deflected same as air being deflected by fan as well. After it deflects through the blade and IPA are moving in circular along with air so this process causing the drug mix with air flow and gain energy to project at target area. Mixing with the air promotes expansion by IPA before it is inhaled into human airway [2]. In the actual case target areas supposed to be human airway but during EFD simulation measured parameter was at the end of cylinder (duct).

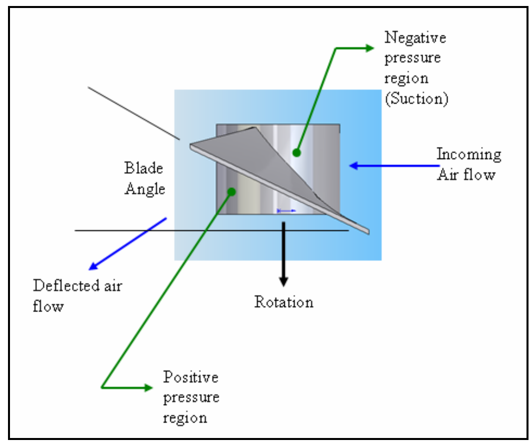

Fig. 3. Airflow deflection by axial flow fan

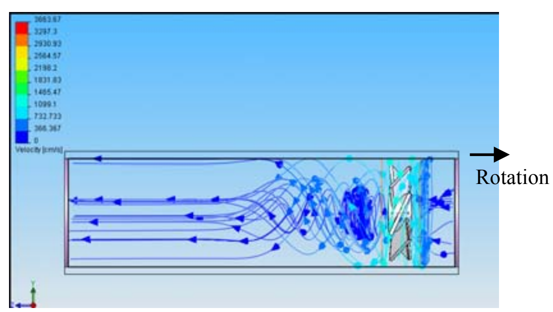

Fig. 4. Airflow trajectories from EED Lab simulation

B. Volume Flow Rate at Varying Angles

Volume flow rate produced by the designed axial flow fan have to be compatible and exceed with the human inhale breathing rate.

TABLE 2
THE HUMAN INHALE BREATHING FLOW RATE

Age		Flow rate (l/min)	Flow rate (m^3/s)
6months			
	sleeping	4.8	0.00008
	low activity	6	0.0001
2years		8.2	0.000137
4years		11.1	0.000185
8years		13	0.000217
Adult male (with mouthpiece)		18	0.0003

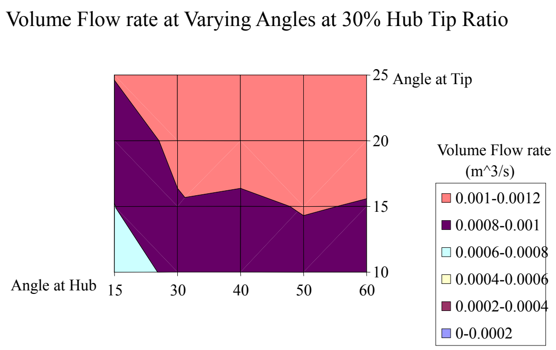

Fig. 5. Volume flow rate at varying angles with 30% hub tip ratio

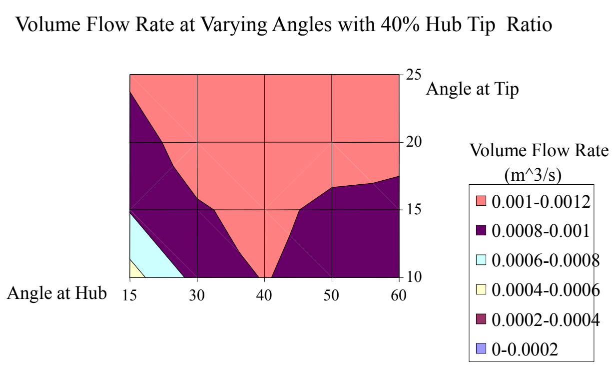

Fig. 6. Volume flow rate at varying angles with 40% hub tip ratio

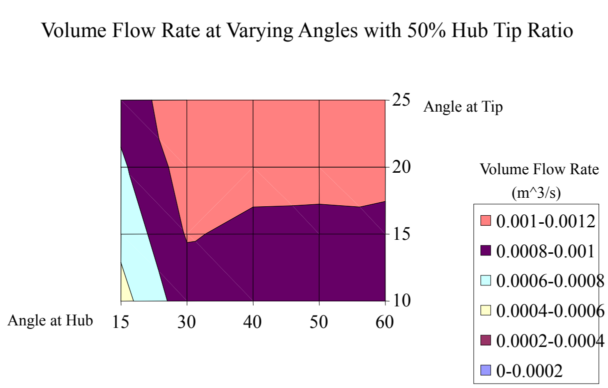

Fig. 7. Volume flow rate at varying angles with 50% hub tip ratio

The figure 5, 6 and 7 explained volume flow rate were exceeded from the human inhale breathing flow rate. The data obtained were exceeding the requirement. Comparing the hub tip ratio figure, 40% hub tip ratio had the highest value at region under the curve. 40% hub tip ratio would give highest value of volume flow rate at hub angle 40°, the entire tip angle having maximum value respectively. This profile was preferred for further modification. More than the range value was acceptable as considering the possibilities would happen as the fan would fit in the spacer.

Figure 8 and 9 shown cross section of spacer design showed these spacers had non constant annular area. But the energy loss due to friction and turbulence would affect more in second design since the second design had more non constant annular area.

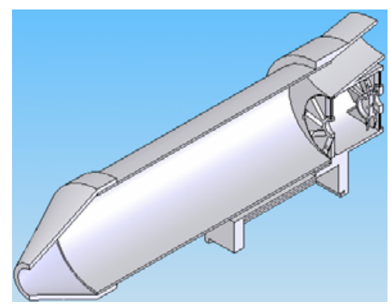

Fig. 8. First spacer design

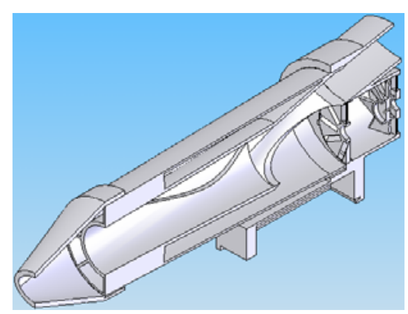

Fig. 9. Second spacer design

Table 3 was the axial flow fan being tested in spacer. The data were in range of volume flow rate required in human inhalation. Therefore the patients were able to reduce the inhaling strength and replace the usage of chemical propellant.

TABLE 3
REDUCTION VOLUME FLOW RATE (m^3/s) IN SPACER

	10000 rpm	15000 Rpm	20000 rpm	25000 rpm	30000 rpm
1st Design	0.0002	0.00039	0.00049	0.00074	0.00063
2nd Design	0.00032	0.00048	0.00065	0.00081	0.00097

C. *Total Pressure and Compression Effect*

High total pressure is required so there is sufficient energy to compress Inhale Pharmaceutical Aerosol (IPA) into human airways. Comparing from figures below, at high tip angle gave high total pressure value. High at angle hub would give high total pressure as well. A small hub diameter could be critical. It might result inadequate performance of the inner blade portion i.e. turbulence and possible reversed air flow near the hub. This inadequate performance was called stalling [1]. 40% hub tip ratio and 50% hub tip ratio gave high compression effect. 40% hub tip ratio with angle at hub 50° and 60°was not referable due to sudden pressure drop and would possibly provide unstable condition in space. The sudden drop might cause pressure fluctuation during fan in rotating condition.

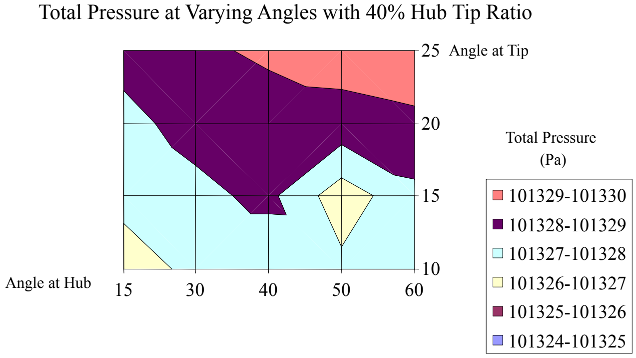

Fig. 10. Total pressure with varying angles at 40% hub tip ratio

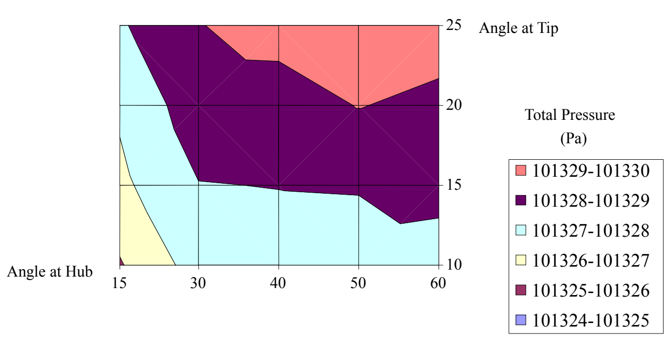

Fig. 11. Total pressure with varying angles at 50% hub tip ratio

D. *Wider Tip*

The best profile was selected as shown in table 4. The designs were modified by increase the tip length by more than 50%.

TABLE 4
SELECTED PROFILES FOR MODIFICATION

Series1	30% hub-tip ratio with hub angle 40° and tip angle 25°
Series2	30% hub-tip ratio with hub angle 50° and tip angle 25°
Series3	40% hub-tip ratio with hub angle 30° and tip angle 25°
Series4	40% hub-tip ratio with hub angle 40° and tip angle 25°
Series5	40% hub-tip ratio with hub angle 50° and tip angle 25°

The purpose to modify these designs was to increase the volume flow rate and total pressure values. Static pressure was essential while designing the axial flow fan and had important relationship within this formula.

$$SP = 3.43 \times 10^{-9} \times rpm \times z_B \times C_L \times l \times W \qquad (2)$$

Where SP = static pressure, in inches of water column
z_B = number of blades
C_L= lift coefficient of airfoil at the angle of attack used at this radius
l = blade width at this radius in inches
W = air velocity relative to the rotating blade in feet per minute (fpm)

This equation 2 indicated again that a larger hub diameter would result in a larger static pressure because for a larger hub diameter. Referring to figure 12, series 4 was among the best curve as the curve continued to increase by speed without any fluctuation as such series 3. Series 3 gave high total pressure at speed 20000 rpm but reduced at 25000rpm then would again increase at high rate at 30000rpm. This fluctuation was possibly occurred due to stall. This verified the equation 2 as series 4 (40%) had bigger hub diameter than series 3 (30%). Large hub diameter gave the best result as the relative velocity W would be larger (due to increased blade velocity) and there would be more room available for wider blades without overlapping.

Since the relative air velocity W was smallest at the hub, this must be compensated by any larger $l \times C_L$ at the hub but both l and C_L can be increased only up to a certain limit (l up to the point where the blades would overlap and C_L up to the maximum lift coefficient the airfoil can produce). The pressure produced as mentioned before was proportional to the product $z_B \times l$. At the hub, the blades must be non overlapping for two reasons: Overlapping blades might choke the airflow. Usually, overlapping blades would be avoided if the blade width was smaller than $l \leq 3.4d/z_B$, where d was the hub diameter and z_B was number of blades. This then would be the blade width at the hub [1].

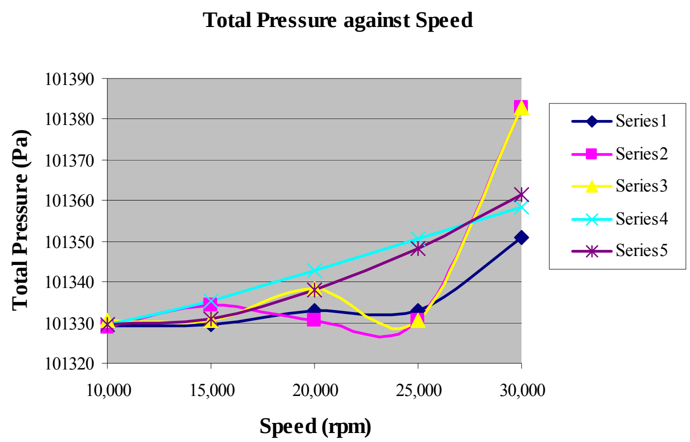

Fig. 12. Total pressure against speed

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E. Number of Blades

A study of wider tip gave 2 best designs was selected for further analysis. Those 2 best designs would be modified into (6 blades, 7 blades and 8 blades) and analyzed at various speeds.

- 40% hub-tip ratio with hub angle 30° and tip angle 25°
- 40% hub-tip ratio with hub angle 40° and tip angle 25°

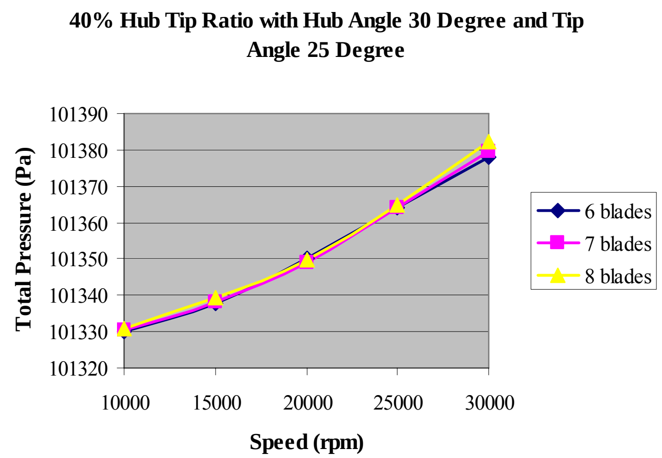

Fig. 13. Total pressure against speed (rpm) at 40% hub tip ratio with hub angle 30° and tip angle 25°

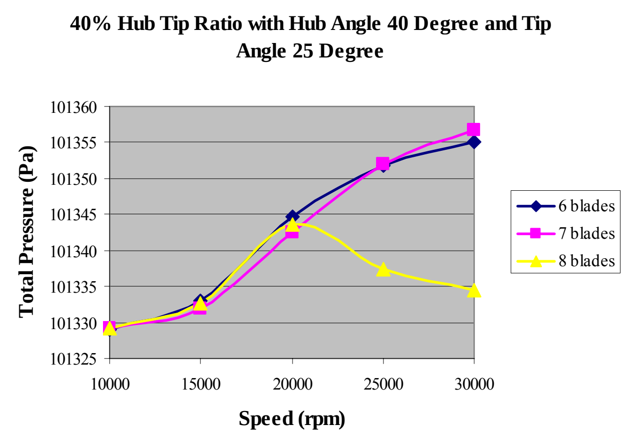

Fig. 14. Total pressure against speed (rpm) at 40% hub tip ratio with hub angle 40° and tip angle 25°

Both figures 13 and 14, 40% hub-tip ratio with hub angle 40° and tip angle 25° at 8 blades gave a negative slope as the speed increased from 20000 rpm to 30000rpm. This was due to the overlapping blade might choke the air flow. But 40% hub-tip ratio with hub angle 30° and tip angle 25° didn't has any negative slope so this design was preferable. The curve for 6 blades, 7 blades and 8 blades were almost equal.

F. Efficiency at Fewer Blades and Wider

The equation 2 for static pressure produced, we already knew that this pressure was proportional to the product z_B x l, the number of blades times the blade width, this means that a certain design can be modified by, for instance, doubling the number of blades and reducing the width to one half.

A study number of blade state that possibly 6 blades was the best design because it had wider tips since it had bigger l value [1.] Let's validate whether this was true by determining the efficiency for 6 blades and 7 blades. Efficiency on 40%

hub-tip ratio with hub angle 30° and tip angle 25° was carry out at various speeds using equation 3.

The fan efficiency at this point of operation would be mechanical efficiency (ME) also called total efficiency.

$$ME = \frac{ahp}{bhp} \quad (3)$$

Where ME = mechanical efficiency
ahp = air horsepower
bhp = brake horsepower

Air horsepower (ahp) was the power output of the fan.

$$ahp = \frac{cfm \times TP}{6356} \quad (4)$$

Where cfm = volume flowrate in cubic feet per minute
TP = Total pressure in (inWC)

Those power produce from DC motor can easily obtained into brake horsepower (bhp) using the equation 5 and at this operating condition assume the motor efficiency or electic efficiency is 0.88.

$$bhp = \frac{W \times EE}{746} \quad (5)$$

Where W = motor electric power
EE = electric efficiency

TABLE 5
COMPARISON ON EFFICIENCY FOR 6 BLADES AND 7 BLADES DESIGN

	Speed (rpm)	Air Horsepower (ahp)	Brake Horsepower (bhp)	Mechanical Efficiency (ME) %
6 Blades	10000	0.00000883	0.00003098	25.07
	15000	0.00003369	0.00003098	95.70
	20000	0.00008516	0.00007789	96.22
	25000	0.00017678	0.00018940	82.14
7 Blades	10000	0.00000852	0.00003098	24.21
	15000	0.00003309	0.00003098	93.99
	20000	0.00008342	0.00007789	94.25
	25000	0.00017188	0.00018940	79.86

Based on the table 5 whereby the 6 blades gave high efficiency than 7 blades. The 6 blades efficiency reached maximum at speed 20000 rpm that was 96.22%. Fewer and wider blades would result in better fan efficiency. On the other hand if the number of blades became too small and the blade width therefore too large the fan hub became too wide axially and thus heavy, bulky, expensive and hard to balance. Aerodynamically the optimal number of blades would be one very wide blade, draped around the entire hub because this would keep the number of blade edges and turbulence less to minimum. One wide blade therefore would result in the best efficiency and in the lowest noise level but in an impractical and costly fan wheel. As a compromise between efficiency and cost, five to twelve blades were good practical solutions [1].

IV. CONCLUSION

The design at 40% hub-tip ratio with hub angle 30° and tip angle 25° in 6 blades is the best design and will fit in the spacer and also increase IPA delivery effectively. After designing the suitable fan for inhaler, there are several factors the successfully achieved and reach the objectives.

- High total pressure causing more compression effect therefore it will increase drug delivery to human airway.
- Volume flow rate produce by designed fan are compatible with human inhale breathing at different gender and various ages so that patient does not require high inhale breathing strength when using this new design spacer.
- Achieved high efficiency at various speed.

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