Advances in Manufacturing Technology XXX
Y.M. Goh and K. Case (Eds.)
IOS Press, 2016

doi:10.3233/978-1-61499-668-2-263

Design Optimisation of Passive Humidification Device for Intensive Care Medical Applications

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Abstract. This paper presents the design optimisation of passive heat and moisture exchange (HME) humidification device for intensive care medical applications. Investigation into the state of the art of the technology in use concludes that there are two main artificial HME humidification devices: active and passive device. The passive HME device is the preferred one, due to the ease of use and low cost. However it is not suitable for more than 24 hour use. This is due to a number of challenges such as: device cavity design, limitations of HME materials performance and overall efficiency. This paper presents the outcomes of the research work carried out to overcome these teething issues and presents an optimised cavity design that could improve the HME material, airflow structure and patterns and HME device overall efficiency.

Keywords. Humidification, HME Devices, Intensive Care Applications.

1. Introduction

Maintaining the humidity of 40 mg/l H2O within human system is a critical factor of healthy organs. During surgery and inside the intensive care unit, the patient's upper airway tract is bypassed to assist breathing and enable controlled delivery of medical gases and thus artificial means must be used for humidification [1-2]. The state of the art of current technology in use concludes that there are two main devices: active and passive device. Whilst passive device is preferred due to ease of use and low costs, it is not suitable for more than 24 hour use, due to airflow structures and patterns, performance of HME material [2-7]. This paper presents the investigation carried out into the state of the art of the HME devices technology. This is to identify the major teething issues with the existing devices. The device structure and internal material arrangements are covered in section 2, section 3 focused on the computer modelling and analysis for the device various material arrangements, the design optimisation of the device is presented in section 4, section 5 presents the results, discussion and findings.

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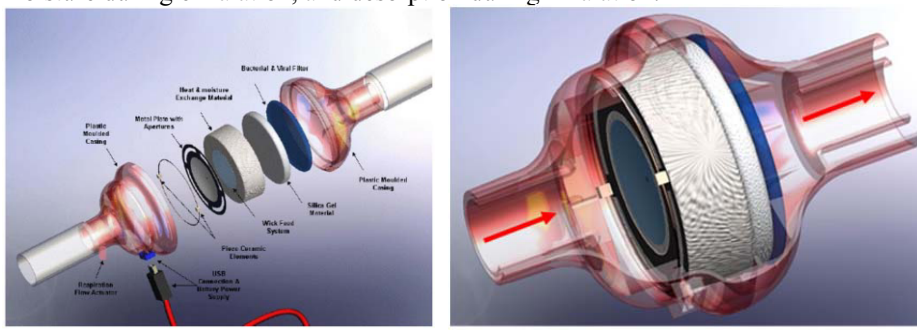
2. Passive HME Humidification Device Structure

The HME humidification device main units and structure is shown in Figure 1 (a) – (b). The device is composed of a plastic cavity in two halves enclosing successive layers of materials. These materials include: A filter restricting the passage of contaminants, bacteria and viruses, HME Materials operating through the sorption of heat and moisture during exhalation, and desorption during inhalation.



(a) (b)

Figure 1. Humid device (a). Units, mechanical and electrical interfaces including casing, (b). Overall assembled structure

3. Modelling and Simulation of HME Humidification Device

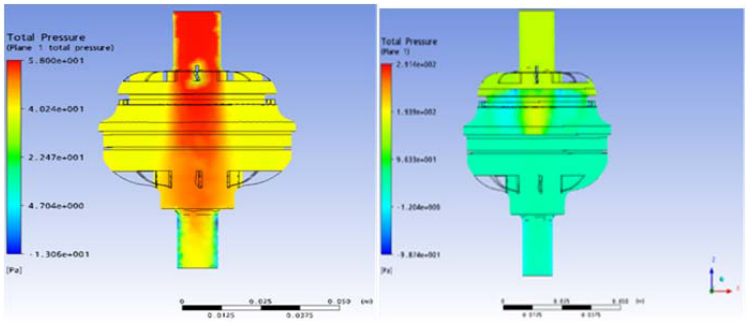
Airflow studies of the HME humidification device have been undertaken using the ANSYS multi-physics software. The main objective of this analysis is to assist in understanding the optimal cavity design with structural geometries; generating improved airflow patterns over target HME material structure(s). Three different materials arrangements have been used, in order to analyze the influence of each component on the airflow pattern. The internal volume of the plastic casing is represented as a pure 3D fluid domain while the filter and HME materials, are represented as porous media. The properties of the different materials used, in this research are included in table 1.

Table 1. The properties of the different materials layers used in the CFD models

Components	Geometry	Porosity
Filter	Ø60x3	Porosity:0.11 (experimental measurements)
Wound paper	Ø50x16	Porosity: 0.10 (does not reflect the ribbed structure of the paper)
Foam	Cartridge weight=6g Volume=16x2400x0.1 mm^3 occupying a total volume of Ø50x16mm^3	Porosity: 0.10 (experimental measurement)

Specifications and Model Development: Airflow analysis has been undertaken considering a continuous airflow of 60l/min going through the device with air entering from the patient side. The direction of the flow for Computational Fluid Dynamics (CFD) analysis was chosen in accordance with the methodology of the test IWI1016 and IWI9300 currently in use to evaluate the performance of such devices. Model development: In order to carry out the CFD analysis, the devices internal volume has

been subdivided into a multitude of small elements called a mesh. Results are then obtained for each individual element. Meshing: The tetrahedrons method with Patch Conforming (Delaunay) Algorithm has been used to mesh the volume. In this method, faces and boundaries (edge and vertices) are respected and an expansion factor setting controlling the internal growth rate of tetrahedrons with respect to boundary size is also included. Definition of the Domains and Boundaries Conditions: The characteristics of the various domains (pure fluid domain, porous domains) and boundaries (inlet, outlet, and wall) are carefully considered and more information can be find in [8]. Simulations: The solutions of the fluid dynamics analysis involve calculations of the airflow velocity, pressure and turbulence including eddy dissipation/kinetic energy distributions. The results of the simulations performed showed that: (i). Plastic moulded Casing: Initial simulations have been carried out on the plastic cavity with no material incorporation. The results of the pressure, airflow velocity and turbulence distributions are presented in figure 2 (a). The observed effect as shown in Figure 2 (a) is due to the non-aerodynamic design of the outlet. As the airflow enters the main cavity of the device, it will expand to the whole cavity and the pressure would be expected to drop. However, the fluid will then encounter a resistance to flow at the base of the outlet as the diameter of the cavity is reduced leading to a pressure increase. The observed effect represented the averaged pressure after equilibrium. Overall, the pressure falls between the inlet and outlet by 35Pa with an observed 50% decrease of the pressure between the inlet and outlet. Patterns of the airflow velocity within the internal volume of the cavity showed airflow mainly concentrated through the centre of the device. The non-aerodynamic design of the outlet can be observed: a sudden diameter decrease at the base of the outlet creates a wall that prevents the smooth circulation of air out of the device. This generates a horizontal airflow that creates turbulences at this level which further decrease the effective outlet diameter. Turbulences occurred are mainly observed as the airflow escape the device. These turbulences are correlated with the resistance to flow exerted at the outlet. (ii). Cavity, Filter & HME Material: Simulations have also been carried out for the plastic casing incorporating a filter and for the plastic cavity incorporating a filter and HME material. Figure 2 (b) shows the pressure distribution for this arrangement. The pressure in the top part of the device is increased by a factor 5 due to the resistance to flow induced by the filter and HME material.



(a) (b)

Figure 2. (a). Pressure distribution for the internal volume of device (a). The plastic moulded casing (b). Incorporating a filter and HME material

The velocity studies shows that the air is still flowing mostly vertically along the z-axis and through the center of the HME material with minimum flow in the external

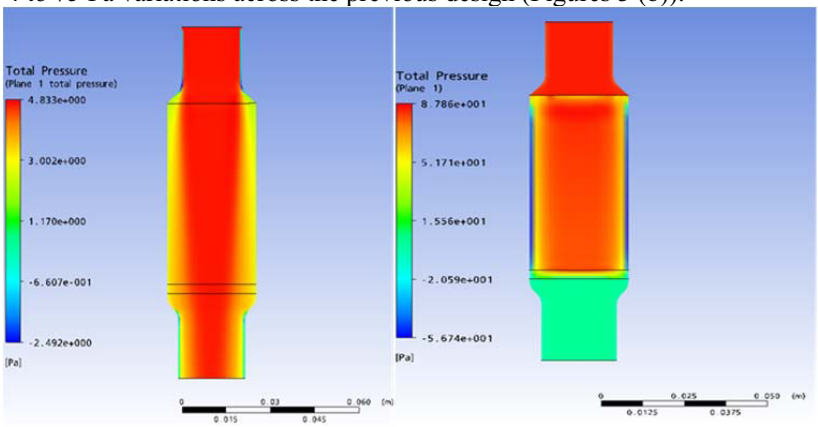
areas of the HME. The velocity patterns demonstrate a limited airflow in the sides of the HME material and filter. This restriction limits the utilization of the materials to their full capabilities. Turbulence analysis shows the front of the air flow within the HME materials. The significant resistance to flow can be observed at the bottom of the device suggesting that a modification of the outlet design could improve the airflow.

4. Passive HME Humidification Device Design Optimization

Modifications of the design have been tested in order to improve the distribution of the airflow in the sides of the cavity and to limit the pressure build up and resistance to flow at the outlet. The first modification of the design involves a large inlet, i.e. the opening of the inlet. The main objective of this modification has been the improvement of the airflow distribution throughout the cavity. The pressure drop between the inlet and outlet is equal to 30.7Pa and is slightly under (-12%) the pressure drop obtained with the initial design. The pressure increases in the cavity (+25%) due to a larger airflow distribution and difficulties to escape the narrow outlet. A larger spread of the airflow can be observed at the inlet. Turbulences can still be observed in the bottom part of the device due to the significant diameter decrease of the outlet. The second modification involves both a large inlet and outlet. The modification aimed to reduce the resistance to flow and pressure drop between the inlet and outlet. Opening of the outlet led to a significant decrease (-86%) of the pressure drop. It was clear that widening and tapering of the inlet and outlet lead to an improved airflow pattern, their design renders difficult the connection of the device with other components. An alternative design has been investigated in an attempt to overcome this issue. The use of Ø22mm inlet & outlet tubing has been studied solving the connection problem while maintaining the same level of performance. The design has therefore been slightly modified to increase the inlet and outlet internal diameters from ≈15 to ≈22mm. Increasing the inlet and outlet tubing diameter from 15mm to 22mm leads to a significant reduction of the pressure within the device. The widening of the inlet and outlet led to the significant reduction of the pressure drop from 35Pa to -0.72Pa. It can be clearly observed from the pressure, velocity and turbulence patterns that the enlargement of the outlet greatly facilitates the airflow through the device. As the spread of the airflow is mainly related to the diameter of the inlet, this alternative design also slightly improve the airflow distribution through the device. It is, however, apparent from the vertical airflow pattern, that the cavity sides are not ventilated.

A radical change in the design (Long Tube Design) has been considered to overcome the central high pressure (Figure 3). The results of the simulations performed on alternative designs with different materials arrangement showed that: (i). Plastic Cavity: Similar level of pressure (Figure 3 (a)) can be observed between the inlet and outlet leading to a very low pressure drop (0.3Pa). Low variations of the pressure drop can be observed in the different parts of the device. The velocity patterns show a uniform airflow inside the cavity and through the whole volume of HME material. Small horizontal airflow and turbulence can be observed at the basis of the inlet and outlet due to a small widening of the device diameter. (ii). Plastic Cavity, Filter and HME Material: A pressure drop of 80Pa is observed with the device. Uniform pressure can be observed in the different parts of the devices and within each layer of materials. High pressure can be observed in the top part of the device due to the resistance to flow induced by the HME material and filter. However, this is only

slightly higher than the previous 67 Pa pressure drop obtained with the original device modified with ID 22mm connectors. As expected, the pressure and flow conditions within the new design are much more homogenous averaging around 80 Pa compared to the 4 to 75 Pa variations across the previous design (Figures 3 (b)).



(a) (b)

Figure 3. Pressure distribution for the internal volume of the device (a). Plastic moulded casing (**b).** Plastic moulded casing incorporating a filter and HME material

5. Experimental Results and Discussions

Simulations carried out on the initial design showed an airflow mainly concentrated through the centre of the device, leading to a limited utilisation of the HME materials in the sides of the cavity. Integration of the filter and HME material in the device demonstrated a slightly improved airflow spread. However, these additional components did not homogenize the airflow to the HME material in the device. Experimental measurements have been carried out in parallel to the simulations. The results of the pressure drops for the housing only, housing & filter and housing, filter and HME material are presented in table 2 along the simulation results.

Table 2. Pressure drop results for different materials arrangements

F/HME component	ISG Current design 1341 (experimental measurement)	Simulation	Variations
Housing only	26 Pa	35.6 Pa	+37%
Housing + Filter	235 Pa	113.8 Pa	-48%
Housing + Filter + HME	288 Pa	197.3 Pa	-31%

The results demonstrate a significant increase of the pressure drop with the insertion of the filter and HME material. Significant variations between the theoretical and experimental data can be also observed. These variations are due to slight geometry variations between the device being simulated and the devices tested experimentally. The permeability properties of the porous media (filter and HME material) have also been measured experimentally by the water displacement and compressive volume methods. However, both methods have relatively uncertainty due to the small volumes of the materials tested. The results for the pressure drop for different designs and

materials arrangement is shown in table 3. This showed that optimised design proved to be very successful.

Table 3. Results for the pressure drop for different designs and materials arrangement

Initial Design	**Pressure drop (Pa)**
Casing	35.6
Casing & filter	113.8
Casing, filter & HME	197.3
Ø22mm inlet & outlet optimized design	
Casing	0.21
Casing & filter	52.9
Casing, filter & HME	67
Second alternative design: Long tube	
Casing	0.72
Casing & filter	46.24
Casing, filter & HME	79.76

6. Conclusion

Design optimisation of the HME humidification device has been presented in this paper. Airflow structures and patterns within the device were the main parameters to consider. The results of the CFD simulations and experimental tests carried out on different designs and materials arrangements showed that the factor limiting the smooth flow of air through the device is the cavity design. This is showed that improving the airflow distribution to the sides of the cavity and through the sides of the HME materials could lead to improved heat and moisture exchange properties of the device. Three designs solutions are proposed and investigated in this paper. The designs based on widening the inlet and outlet and that based on long tube have shown a very good improvement and enhanced the airflow structures and patterns, heat and moisture of the HME device.

7. Acknowledgements

The authors would like to thank EC FP7 and HUMID consortium, for their support and dedication to deliver such an outstanding work and improve people quality of life.

References

[1] Y. Chikata, J. Oto, M. Onodera and M. Nishimura, Humidification Performance of Humidifying Devices for Tracheostomized Patients With Spontaneous Breathing: A Bench Study, *Open Forum of the 58th AARC Congress*, New Orleans, Louisiana, 2012.

[2] Y. Chikata, C. Sumida, J. Oto, H. Imanaka and M. Nishimura, Humidification Performance of Heat and Moisture Exchangers for Pediatric Use, *Critical Care Research and Practice* 2012.

[3] G. Eason, B. Noble and I.N. Sneddon, On certain integrals of Lipschitz-Hankel type involving products of Bessel functions, *Philosophical Transactions of the Royal Society of London* **247** (1959), 529–551.

[4] J. Clerk Maxwell, *A Treatise on Electricity and Magnetism*, Oxford: Clarendon, 68–73, 1892.

[5] I.S. Jacobs and C.P. Bean, Fine particles, thin films and exchange anisotropy, in *Magnetism*, Vol. III, G. T. Rado and H. Suhl, (eds.), New York, Academic, 271–350, 1963.

[6] Y. Yorozu, M. Hirano, K. Oka and Y. Tagawa, Electron spectroscopy studies on magneto-optical media and plastic substrate interface, *IEEE Translation J. on Magnetics in Japan* **2**, (1987), 740–741.

[7] M. Young, *The Technical Writer's Handbook*. Mill Valley, CA: University Science, 1989.

[8] M. Shafik and A. Lechevretel, Computer Simulation and Modelling of Passive Humidification Device Cavity for Intensive Care Patient Medical Applications, *ASME 2014 International Mechanical Engineering Congress and Exposition*, 2014.