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Vibration Evaluation and Gas Transfer of Distilled Water and Bovine Blood in Intravascular Lung Assist Device using PZT Actuator

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1. Introduction

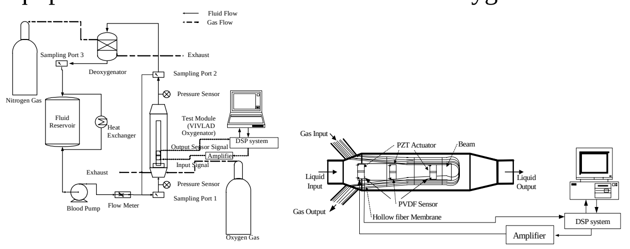
Acute respiratory distress syndrome (ARDS) is a form of acute respiratory failure caused by extensive lung injury following a variety of catastrophic events such as shock, severe infection, or burns. ARDS can occur in individuals with or without previous lung disease. The disease affects approximately 150,000 people per year in the United States [1]. Its treatment requires respiratory support using the conventional therapies of mechanical ventilation, or extracorporeal membrane oxygenation (ECMO) in patients with severe ARDS.

Intravascular oxygenation represents an attractive, alternative support modality for patients with ARDS. The concept of intravascular oxygenation as an alternative ARDS therapy originated with Mortensen [2], who developed an intravenous oxygenator (IVOX) consisting of a bundle of crimped hollow fiber positioned in the vena cava. In clinical trials, the IVOX provided an average of 28% of the basal gas exchange requirements for patients with severe ARDS [3]. In an intravenous membrane oxygenator, the greater part of the oxygen transfer resistance is located in the blood-side laminar film [4], and various methods have been tried to make the laminar film thinner and improve the oxygen transfer rate [5,6]. In the present study, the water flow characteristics in the implantable artificial lung were evaluated by in vitro experiments methods [7-9].

In this paper, an analytical solution were developed for the hydrodynamics of the flow through a bundle of sinusoidally vibrated hollow fibers to provide some insight into how wall vibrations might enhance the performance of an intravascular lung assist device. Scaling analysis was then used to infer the dimensionless groups that correlate the performance of a vibrated hollow fiber membrane oxygenator. The experimental design and procedure are then given for a device for assessing the effectiveness of membrane vibrations.

2. Experiment

The measurements were performed by the AAMI/ISO international standard recommendations [10]. The experimental closed loop was primed with less than 6 liters of fresh filtered cattle blood after addition of 75 ml ADC and 1 ml heparin as anticoagulants. The hemoglobin content was calibrated to the required value (12.0±1.0 g/dl) by dilution of the blood with normal saline. Adequate recirculation was performed before the test, to adjust the blood's inlet conditions to those of the AAMI/ISO standards. The test lasted six hours. Gas flow rates of up to 6 l/min through the 120-cm-long hollow fibers have been achieved by exciting a piezo-vibrator with a sinusoidal wave magnitude of DC 50 V. Fig. 1 shows the experimental setup of the testing equipment for measurement of the blood oxygen transfer.



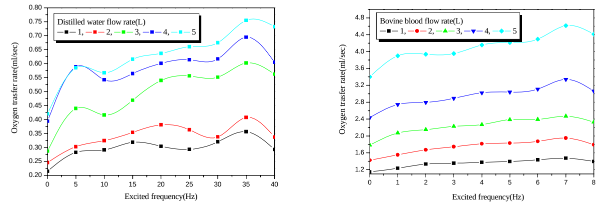
(a) in-vitro bench test system (b) intravascular lung assist device (ILAD)

Fig. 1. Experimental set-up for the vibration measurements.

The signal processing of the data was carried out using a DSP 1104 board (TMS320C40, dSPACE GmbH, Germany) and an amplifier (SQV 3/150, Pizomechanik Dr. L. Piekehman GmbH, Germany). The signal from an A/D converter, with a sampling ratio of 1ms, was sent to the DSP system and the calculated input voltage to a PZT actuator, for exciting the test module through the D/A converter and amplifier. The signals from the sensor, according to the applied input voltage, were digitalized and filtered in order to obtain the dynamic characteristics of the composite beam in the artificial lung device. In the filtering operation, the DC offset was rejected and the noise eliminated by band-pass filters (BPF) with the cutoff frequencies of 0.5 and 50Hz, respectively. Finally, the signals are integrated to take into account the applied input voltage.

3. Results and Discussions

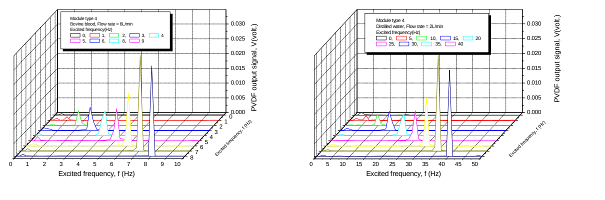
Figure 2 shows the relationships between the oxygen transfer rate on the bovine blood and distilled water with the various excited frequencies. When the excited frequency increases, the oxygen transfer rate increases. However, although the oxygen transfer rate of propagation expressed a maximum when frequency was 7 (when used bovine blood) and 35Hz (when used distilled water), with frequencies greater than 7 and 35Hz the oxygen transfer rate of propagation again show decreasing tendencies. The reason for this could be judged and confirm from figure, where the frequency of 7 and 35Hz expressed a maximum oxygen velocity of propagation as the maximum flicker occurred in the bovine blood and distilled water of the fluid system. The maximum oxygen transfer rate seemed to be caused by the occurrence of the maximum amplitude and transfer of vibration to the hollow fiber when excited by a frequency of 7 and 35 Hz for each flow rate, because this frequency became the 2nd mode resonance frequency of the flexible beam in blood flow.



(a)Bovine blood (b) Distilled water

Fig. 2. Experimental circuit for the evaluation of the oxygen transfer.

Figure 3 shows the output voltage of the PVDF sensor at the maximum oxygen transfer rate in module. As shown in this figure, the maximum amplitude of the PVDF sensor output was at a frequency band of 7 and 35Hz for various flow rates. The maximum oxygen transfer effect occurred at the frequency band of 7 and 35Hz. This resonance effect represented the maximum oxygen transfer rate by reducing the boundary layer, occurring on the surface of the hollow fiber membrane (HFM). From this figure, effective response characteristics about the vibration amplitude can be achieved up to approximately 7 and 35Hz, when the amplitude of the excited input voltage of sinusoidal wave is excited from 0 to 100V to PZT actuator. Here, the signals between 2 to 3 Hz are related to the natural frequencies occurring from the device itself due to the dynamics of the fluid when the fluid is expanded or compressed near the inlet or the outlet. As can be observed from sub figures, the maximum strength of the PVDF sensor output can be observed when the excitation frequency of 7 and 35 Hz is introduced. Moreover, the amplitude of the PVDF sensor output tend to increase as the number of HFM increases due to the decrease in the effect from fluid dynamics. As excitation frequency of sinusoidal wave with PVDF actuator increases, the signal amplitude obtained from PVDF sensor increases from the effect of the actuator. However, the effect of the excitation frequency on the vibration decreases when the excitation frequency is higher than 7 and 35 Hz resulting in the decrease in the oxygen transportation rate. This is due to the fact that there are limited window of the frequencies for efficient propagation of vibration according to the fluid velocity, the number of HFM, and the viscosity of the fluid when the vibration propagated to join the HFM is transmitted to fluid. The effect from the vibration beyond the band of the frequencies was decreased.



(a)Bovine blood (b) Distilled water

Fig. 3. Amplitude of PVDF sensor output for the system with various excited frequencies.

4. Conclusions

One of the most important results of this study is the finding of the increase in the gas transfer rate resulting from the vibration of an intravascular lung assist device. We designed the oscillatory type artificial lung assist device attached with PVDF sensor and PZT actuator, and obtained the following conclusion for improving oxygen transfer rate of the ILAD. We have shown that the efficiency of oxygen transfer of the ILAD consisting of HFM improves according to the approved sinusoidal wave at the PZT actuator in fluid flow. Therefore, the experiment results showed an effective performance for enhancing the gas transfer of the ILAD. The gas exchange efficiency for the ILAD was increased with the following design features: consistent and reproducible fiber geometry, and most importantly, an active means of enhancing convective mixing of distilled water and bovine blood around the hollow fiber membranes.

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