Intelligent Control and Instrumentation for Hollow Fiber Membrane Manufacturing System

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Abstract: The paper describes the development of a hollow fiber membrane (HFM) manufacturing system employing various instrumentation devices to achieve a fully automated system. A programmable logic controller (PLC) is central to the development of the system. It is deliberately designed with the capability to adapt to various circumstances and conditions according to variation changes that are related to membrane materials, room conditions, processes and/or other factors deemed desirable for the human operator. In this study, efforts have been made produce a system that is able to check the properties of the HFMs during the manufacturing process (either online or offline) based on graphical outputs, capability to produce a repetitive and reliable product, potentials to considerably decrease the waste of material and increase productivity (reduce time) via graphical investigation and image processing technique.

KeyWords: Hollow fiber membrane, PLC, Automated system, Membrane surface properties, Image processing

1 Introduction

Investigation of the membrane physical properties is one of the most important recent developments in the membrane separation processes [1]. The membrane has to possess physical properties giving appropriate interactions with solutes in the process stream allowing the optimization of separation performance. The most effective investigation of physical properties is being made by microscopic observation [2].

Membranes have several applications in various fields of science and industry such as gas separation, optimization, desalination of seawater, blood dialysis, filtration of ground and underground waters, filtration of household and industrial wastewater, medicine industry and biotechnology [3]. A membrane is a semi-permeable barrier, which separates mixtures by controlling the rate of transport of a particular component. The membrane has been an emerging technology for the past 25-30 years. These processes present practical advantages over other separation processes [4], such as:

1. energy savings since no phase changes required
2. no chemical reactions required and therefore no chemical alteration
3. the ability to separate temperature sensitive solutions since the separation can be carried out at ambient temperature
4. membrane physical and physicochemical properties are variable and can be adjusted
5. membrane technologies are capable of removing a wide range of contaminants from particulates, including pathogens and ionic species

In general, membrane performance evaluation involves trial-and-error methods encompassing the optimal material formulation, selection of critical operating variables and proper conditions during the fiber spinning process [5]. Although a great deal of work has been conducted in the past, the evaluation of the membrane performances for specific application is still considered a real challenge as it involves a considerably high level of difficulty and intricacy in the system. It also seems that there is a lack of a comprehensive study on the application of a good control system to predict and optimize the membrane fabrication conditions [6].
Therefore, a design of an intelligent control system to produce higher performance membrane and enhance its reproducibility is the key objective of this study. In addition, easy control on the surface porosity, pore size, wall thickness, shape by applying image processing technique of the fabricated HFM are aspects that are deemed to be of considerable interest for further exploitation and study.

2 Methodology
The development of the automated HFM manufacturing system is considered a challenging task as it involves many crucial factors such as a large number of variables/parameters to be manipulated, handling of raw materials, complexity of the HFM production itself and system integration. This invariably involves a full mechatronic approach, i.e., the synergetic combination of mechanical, electrical/electronics and computer control disciplines. Thus, the design of the hardware involving electro mechanical input-output devices linked through computer control software and electronic interfacing is integral to producing a good and reliable automated system. As an initial investigation, a thorough work and time study of the HFM production is essential to grasp the main processes involved. Later, the design of the automated system should be carried out to encompass all the mechatronic elements as mentioned earlier. The more detailed description of the methodology is given in the following sections.

2.1 Hardware and Material Description and Design
A laboratory scale production line to fabricate HFM s by means of dry/wet phase inversion method as the most flexible membrane fabrication method was designed. A mixture consisting of polymer, solvent, non-solvent was provided. The solution was then transferred to a reservoir and pumped to the spinneret. Bore fluid was supplied by another syringe pump into the lumen side of nascent hollow fibers. This system will spin in the single line membrane at a time. The system is capable to operate at speeds up to 30 m/min, and draw or relaxation may be applied to the membrane at any point between the tanks or devices. The details of membrane spinning can be found elsewhere [7, 8]. Note that all the tanks and vessels are accurately temperature controlled. The nascent membranes were then kept in water for three days to remove the residual solvent and non-solvent. The spinning system can be conveniently automated using a programmable logic controller (PLC) and a high resolution camera to monitor the membrane surface and indirectly control its properties simultaneously.

A digital microscopy image analyzer unit then captured the images. The unit is able to obtain high-resolution images (full high definition - FHD) through a high speed data transfer which are connected directly by USB to PC. Fig. 1 shows a schematic diagram of the HFM manufacturing system.

2.2 Sensors and Actuators
Four types of sensors were used to obtain data and conditions of system for spinning machine atomization. This includes temperature, pressure, flow meter and tension sensor The archived data were then transferred to the main PLC unit in order for it to store and transfer the signals to a PC for later computation. Moreover, five types of actuators consisting of gear pump and spinning speed controller (inverter), linear actuator positioner, syringe pump, heater and chiller were applied. The adjusted system is designed in such a way to be adapted by any kind of setting which is demanded by the user.

2.3 Control System
Membrane fabrication system was improved by setting up a control unit of the PLC and inverters, signal conditioners to receive the data and send the response to the actuators. This helps to increase the reproducibility of the membrane. The schematic diagram of the control cabinet of the HFM manufacturing system is shown in Figure 2.

Subsequently, Figure 3 shows the connection diagram of the main control system along with the input and output signals. The feed of the control system is the signals from the sensors which transmit the data to a PC through the PLC.
Furthermore, the images from the high resolution camera were directly transformed to the PC to acquire the physical surface properties of the HFMs by image processing. The coagulation bath temperature, ambient temperature and humidity were also monitored. The collection drum speed was controlled using a tension sensor control which is located before the membrane collection drum. All acquired data were processed by the PC using a computer program written in MATLAB environment based on the initial inputs.

2.4 Image Processing of HFM Surface

In the past, many of the fabricating processes were manually performed based on expected human labor and their vision responses. In this case, the ability of the human visual system was an integral part of the process which may contribute to errors in the final membranes production [9]. By automating the processes, it may in turn require high demand of mechanization and utilization electrical/electronic devices plus computer control elements. This may possibly include the use of an artificial vision system during the membrane fabrication to assure quality control aspect of the HFM manufacturing system. In the proposed study, the artificial vision and the ensuing image processing were carried out in three main functions, namely, control, inspection and log information.

The application of machine vision in inspection is normally related to the determination of some parameters for further course of actions in the manufacturing system [10]. These inspection parameters may be related to the mechanical dimensions and the shape, surfaces, number of holes in a piece, presence or absence of a particular feature that may be inspected by the proposed designed machine vision system.

Thus, a good machine vision system may provide useful information about the quality of the product/material as well as demonstrate its capability to track the related processes effectively. The data is automatically transmitted to the computer database system for analysis and other use. This data entry method is very accurate and reliable in which the human labor is eliminated. In addition, it will be highly profitable since information after inspection is gathered and transferred immediately.

A machine vision system includes all the necessary parts to produce an image, defined as a digital image, change and improvement data via image processing and finally presentation of the digital image data through suitable output/display device. Thus, the main components of the system are image acquisition (capturing) unit, processing unit, displaying unit.

The necessary requirements (resources) for image acquisition are presence of sufficient light intensity, digital camera, computer capture interface card and relevant software program for analyzing and digital processing. Displaying of the information (images) was also done via suitable output screen which can be stationed as an intermediate device. The other components of a machine vision system may include the digital...
controller (PC or PLC based), mainframe integrated computer and also an alarm device.

3 Results and Discussion
The results obtained in the study are analyzed and discussed accordingly in the following sections.

3.1 Processing (Enhancement)
The membrane surface strongly affects its performance in carrying out tasks such as filtering, cleaning, etc. Hence, it is crucial to control the parameters that influence the surface characteristics. The flow rate of the spinning dope, bore fluid rate, collection drum rate were astutely processed by an intelligent control system to give their optimized based on specific applications. The surface images of the membranes were taken by camera (see Figure 4) and analyzed by software. Generally, the images from the outer surface and cross section of a porous HFM is between zero and 255 pixels in which, low pixels were assumed as pore area and pixels with high luminance were assumed as background.

In the first step, the token images were converted to grey images and then resized into square pixels in order to transfer to the computer analyzing. The medfilt2 function was used to filter and eliminate the noises from the images. Then Unsharp algorithm was used to increase the intensity of the images and edges. Before the classification, the images were adjusted to detect the pore boundaries and cross section clearly. As can be seen, there are some blurred defects on the surface of the membrane which became clearly visible after analyzing them through the software. The detected defects on the surface after analyzing them in turn trigger the program to propose a new adjustment of the membrane spinning conditions. In other words, the operator detected all the defects on the membrane surface with high resolution automatic focus vision system which will help membranologists to acquire better and higher quality membrane.

3.2 Measurement
An auto edge detector was applied to find out the diameter of the HFM during spinning. The diameter was compared with the inserted value by the operator. By any difference between those values, the program facilitates an order to change the related actuators. In other words, the system provides a constant membrane diameter during membrane fabrication which by any diameter changes, the related orders will send to stabilize the diameter again. Figure 5 shows a simple example of an auto edge detection of the membrane diameter and the extracted necessary data by image processor software are shown in Table 1.

3.3 Shape Analysis
Shape is the other factor deemed important in assessing the quality of membrane performance. The automatic HFM system can achieve a better result by checking the roundness and cross sectional area of the membrane by applying the proper
setting. Figure 7 shows the detection of the cross sectional area by image processing.

![Fig. 7. Detection of the cross section area by image processing](image)

### 4 Conclusion

The development of an automated HFM manufacturing system has been described. It is capable to be adapted to further changes according to any changes or variation in the membrane material, ambient condition, or other changes deemed desirable by the operator by means of operating the system console. The system also has the ability to check the properties of the HFM during the process of manufacturing (on-line or off-line) through graphical investigation, ability to produce a repetitive and reliable product and improve productivity while considerably reducing the waste of materials.

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