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Impregnated electrospun nanofibrous membranes for water vapour transport applications

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ABSTRACT

Membranes with high water vapour permeance and selectivity find many end uses including protective clothing, dehydration, and humidification. One application for water vapour transport membranes is in energy recovery ventilators (ERVs) for buildings. These devices improve building energy efficiency by transporting heat and moisture between incoming and outgoing air streams in building ventilation systems, effectively 'recycling' the energy used to condition the indoor air. Membranes for these devices must have high vapour permeance, and selectivity for water vapour over other gases and contaminants that may be present in the exhaust indoor air. Due to the high rates of water vapour transport required in these gas to gas devices, boundary layer and internal resistances within the membrane contribute significantly to performance. Commercially available membranes suffer from high water vapour transport resistance in the microporous substrate support layer. In this study we report the fabrication of novel impregnated electrospun nanofibrous membranes (IENM) for water vapour transport applications. Electrospun nanofibre layers are impregnated with a polyether–polyurethane solution and cured to create continuous thin impregnated fibre loaded film layers which are bound to a non-woven support layer. These membranes have high water vapour permeance and selectivity while eliminating the requirement for a microporous support layer which has high vapour transport resistance. Here we report initial studies on how controllable factors in the membrane fabrication (namely fibre loading and impregnated solution polymer solids concentration) affect structural and permeation properties of IENMs created. Membranes with adequate permeance and selectivity are demonstrated and direction for optimization is identified. We find that the nanofibre loading has a significant impact on water vapour permeability as the membrane thickness decreases. Future work will study how modifications to the geometric and structural properties of the fibres affect the membrane performance.

1. Introduction

Nanofibrous materials can be fabricated via the electrospinning process which can generate fibrous materials in the 100–1000 nm diameter range. Electrospinning involves drawing polymer solution from a spinneret needle via an electrostatic potential field. As the polymer jet discharges from the needle tip, the solvent in the solution begins to evaporate; the jet destabilizes and undergoes a whipping motion. This whipping further draws the fibre to thinner diameter before the dry fibres are deposited on the collector. This process can be used to spin fibres from a wide variety of polymeric materials [1–3].

Due to high porosity and high surface area, electrospun nanofibrous materials have demonstrated use in a broad range of applications [4]. In those end uses involving permeation through the fibre layer, nanofibrous materials have been used in "breathable" performance clothing, air filtration, and water filtration. In breathable clothing it is desirable to rapidly transport sweat produced by the body due to exertion, while preventing wind and external moisture from penetrating the fabric. Studies on nanofibrous materials have demonstrated high water vapour permeation rates for performance clothing [5]. Work on nanofibre based air filtration materials has also established that increased permeation rates are related to decreased fibre diameter [6,7]. Research on electrospun nanofibre ultrafiltration membranes has demonstrated that permeation performance may be increased by over a full order of magnitude from previous membranes [8,9]. Other recent work has identified electrospun nanofibrous membranes as promising candidates for osmosis processes [10,11]. However, no reports demonstrate nanofibrous membranes which

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contain a dense selective polymer layer for water vapour transport applications.

Water vapour transport membranes are of interest for gas drying, performance textile, and humidification/dehumidification applications. Work by Metz et al. considered permeation properties of various dense polymers for gas drying and presented an extensive review of water vapour permeability and selectivity in various polymers [12]. Their work focused on PEO–PBT copolymers, PEO containing block co-polymers demonstrate favourable permeability properties for water vapour transport applications, and include families of co-polymers such as polyether block amides (PEBA), polyether–polyurethanes, and polyether-polyesters [13–15]. PEBAx polymer membranes have also been the focus of recent methane dehydration work [16]. Polyether–polyurethanes have traditionally been used in 'breathable' apparel applications, in the presence of water vapour the PEO–PU polymer sorbs water into the 'soft' PEO blocks of the polymer creating 'channels' through which water can migrate, driven by a concentration gradient, while the 'hard' polyurethane segment provide mechanical integrity to the polymer film [17,18].

Another application for water vapour transport membranes is in energy recovery ventilation for buildings. Flat-plate air-to-air energy recovery ventilators (ERVs), known synonymously as enthalpy exchangers, improve ventilated building energy efficiency by transporting heat and water vapour between incoming and outgoing air streams in buildings, effectively 'recycling' the energy used to condition building air, see Fig. 1. In modern buildings, ventilation systems are used to exhaust stale air, and bring in fresh air. In 'cooling' conditions for example, the incoming 'outside' air is hot and humid, and the 'indoor' exhaust air is cool and dry. Most of the energy used in air conditioning is expended condensing water vapour, so by passing the cool dry exhaust air over one side of a permeable membrane, and the hot humid incoming air over the opposing side of the membrane, the exhaust air can be used to precool and dehumidify the incoming air. In 'heating' conditions (North American winters), the enthalpy exchanger operates in the opposite direction, incoming cold air is preheated with outgoing warm exhaust air, and moisture is transported through the membrane from the exhaust air to humidify the incoming air. The use of these devices can have a significant impact on building heating and cooling efficiency, recovering over 60% of the total energy exhausted from buildings, while improving indoor air quality and comfort [19,20]. The overall 'effectiveness' of these enthalpy exchangers is defined in terms of sensible (heat transport) and latent (moisture transport) effectiveness [21]. Membranes for these devices must have high water vapour permeance and be selective for water vapour over other gases and contaminants that may be present in the outgoing indoor air. Transport of gases and contaminant chemical species from the exhaust air through the membrane would contaminate the incoming building fresh air. This would decrease the overall function of the exchanger, as ventilation aims to exhaust the stale air. The membrane is a key component of the enthalpy exchanger core, and the focus of the present work.

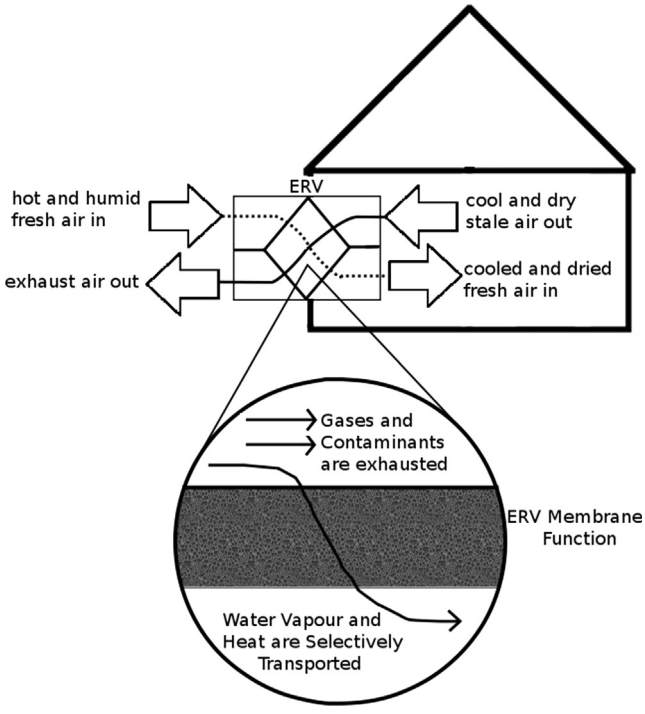

Fig. 1. Function of ERV system and membrane with a hot and humid outdoor environment (cooling conditions).

The literature contains reports of the development and testing of a number of membrane materials and exchanger designs for ERV devices. The most extensive body of work completed in this area is that of Li-Zhi Zhang at the Laboratory of Enhanced Heat Transfer and Energy Conservation at South China University of Technology. Early work by Zhang reports the permeation testing of porous mixed cellulose and cellulose acetate films to determine the moisture diffusivity for use in an energy recovery ventilator model [22]. The membranes in the study are not selective and are not specifically designed for the application. In a later study, Zhang and coworkers built ERV cores from these membranes and confirmed that these polymer membrane cores had much improved exchange effectiveness over paper-based cores [23]. They do not state whether the materials are selective for water vapour over other permeants. It is a requirement of these cores to not allow gases and contaminants other than water vapour through the membrane. Later Zhang reported the development of membranes for ERV applications using a porous PES substrate with a polyvinyl alcohol coating containing lithium chloride [24]. It was reported that increasing hygroscopic LiCl content increased the permeation rate of the membrane material. No selectivity or gas crossover results are reported for these materials, and LiCl being a salt is likely to leach out of the membrane on contact with water, which will decrease the useful operational regime, lifetime, and washability of the material. Hwang et al.. reported that sulphonated styrene–ethylene–butylene–styrene (SEBS) tri-block co-polymers had high water uptake and high water vapour transport, suggesting that membranes fabricated from sulphonated SEBS might be promising candidate membranes for ERV applications [25]. A study by Min et al. analysed the vapour transport properties of microporous polyethersulfone (PES), polyvinylidene fluoride (PVDF), and cellulose, with 0.22 μm pore size and a thickness of 100 μm [26]. They reported that the membranes with higher sorption coefficients also demonstrated higher water vapour transport. These results are for porous materials, and the membranes are not selective; however there is an indication that improved sorption in the substrate will also improve the permeation performance. Zhang et al. more recently fabricated asymmetric cellulose acetate membranes for ERV applications by a wet phase inversion technique, demonstrating a selective membrane that was permeable to water vapour but not other gases [27]. They found that in order to decrease the CO_2 transfer rate to a sufficiently low level, the dense layer had to be quite thick (>2 μm) and consequently the water permeation decreased significantly (by over 50%) in these materials. Another recent study demonstrated the permeability of water vapour and other volatile organic compounds (VOCs), and the selectivity of water vapour over VOCs in a number of polymers [28]. Evidently there is a trade-off between selectivity and water vapour permeation