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Thermoplastic Composite Heat Recovery Ventilator

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By

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Abstract

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Heat recovery ventilation continues to increase in importance as building codes mandate reduced air infiltration and increased energy efficiency. Heat recovery ventilators are able to reduce building heating and cooling loads by transferring heat between the exiting air and incoming ventilation air. In the role of heat recovery ventilation, additively manufactured polymer composite heat recovery ventilators offer significant advantages over traditionally manufactured metallic alloy heat recovery ventilators. Through the implementation of additive manufacturing, the internal geometry of the heat recovery ventilator can be optimized to decrease the head loss across the system and features to improve heat transfer such as fins can be added without increasing the number of manufacturing steps. The advantages of using a polymer composite are that polymer composites are compatible with fused deposition modeling, have thermal conductivities high enough to make a practical heat exchanger, and are chemically stable in wet environments. The creation of an additively manufactured polymer composite heat recovery ventilator is feasible.

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Chapter 1

INTRODUCTION

As updated building codes mandate increased insulation and decreased air infiltration, the need for controlled ventilation has increased as compared to buildings built to older building codes. The amount of uncontrolled air infiltration is small enough in modern buildings to require ventilation in order to help prevent sick building syndrome [1]. In buildings built to modern building codes, a large portion of the heating and cooling load is used to heat or cool the incoming ventilation air. Heat recovery ventilation is able to reduce heating and loads by exchanging heat between the incoming air stream and the outgoing air stream. In the winter when the building is being heated, the exiting air stream is hotter than the incoming ventilation air so heat is transferred from the outgoing air to the incoming ventilation air. In the summer the process is reversed and heat is transferred from the incoming ventilation air to the outgoing air stream. Some of the energy that can be recovered by the heat recovery ventilator is from the latent heat of the water that condenses inside the heat exchanger [2]. Regardless of whether or not it is desired that water vapor condenses in the heat exchanger, it is nearly unavoidable when the temperature gradient between the inside and outside of the building is substantial. This condensing water is always on the warmer side of the heat exchanger, so in the winter the condensation is on the side of the departing air stream and in the summer the condensation is from the incoming ventilation air. This conventional method of heat recovery ventilation is capable of substantially reducing the heating and cooling loads of modern buildings.

Traditionally the materials that have been chosen to construct the heat exchangers in a heat recovery ventilator are metal alloys due to their high thermal conductivity and corrosion resistance [2]. The heat exchanger arrangement that is most commonly used in residential heat recovery ventilators is the cross-flow type as this type of heat exchanger can transfer a large amount of heat per surface area but has lower potential effectiveness than a counter flow arrangement [3]. Another reason that this style of heat exchanger is used is that they can fit a large amount of surface area in a small overall volume [3]. A common method of constructing a cross flow heat exchanger inside of a residential heat recovery ventilator is a series of parallel flat plates made of a conductive alloy where the airstream between the plates is prevented from mixing by a series of channels. This method can be seen in figure 1 [3].

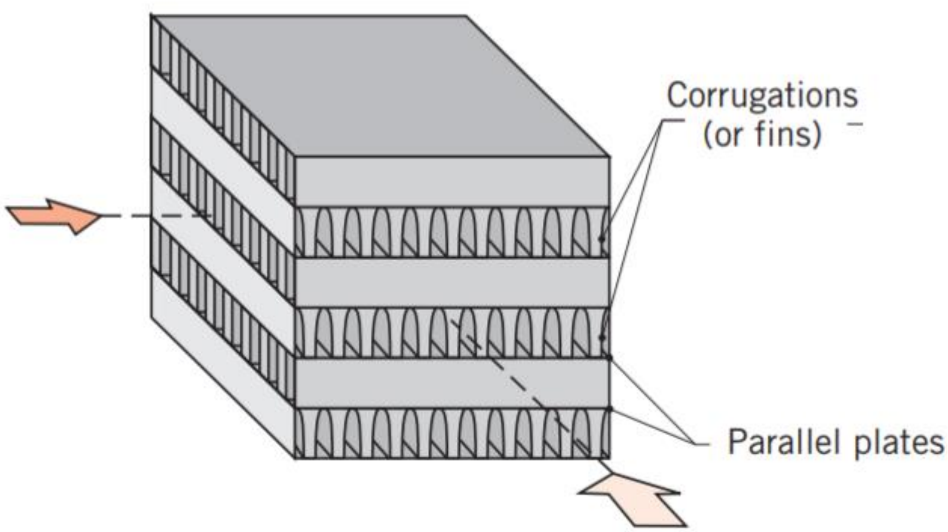

Figure 1: Crossflow parallel plate heat exchanger [3]

This method of construction is commonplace due to the ease of which it can be constructed using traditional manufacturing methods. The crossflow arrangement is also used as it simplifies the manifold design needed to supply air to the heat exchanger. This simplification of the manifold design reduces the cost of manufacturing crossflow heat exchangers as compared to counter flow types. Traditional heat recovery ventilators are able to substantially decrease the heating and cooling loads of a building that they are installed in while preventing sick building syndrome by supplying ventilation air [1]. If building codes continue to mandate higher levels of insulation and tighter building envelopes, the importance of heat recovery ventilation will continue to grow.

Advances in polymers and additive manufacturing have made polymer-based heat exchangers an interesting alternative to the traditional metallic heat exchangers. The additive manufacturing method that has great potential for its use in polymeric heat exchangers is fused deposition modeling, as it is able to print a large variety of materials including composite materials. Fused deposition modeling works by feeding a thermoplastic filament into a nozzle where it is melted and extruded onto the previous layer of the print [4,5]. The heat of the layer that is being extruded melts the top of the previously extruded layer binding the two layers together [4]. When printing the part is constructed layer by layer this results in a higher strength in the plane defined by the bed of the printer than the direction perpendicular to the print bed [5]. This isentropic behavior is due to the fusing between the layers in the print not being as strong as the continuous strands of thermoplastic in the x, y plane [5]. Another reason to focus on fused deposition modeling is that the machines used for this method are relatively accessible.

Another additive manufacturing method that could be feasible is stereolithography as it is another additive manufacturing method that was developed for use with polymeric materials. Stereolithography uses a photosensitive polymer and an ultraviolet light source that selectively hardens the photopolymer [5]. A potential advantage of stereolithography over fused deposition modeling is the improved resolution [5]. The reason that resolution is important it that it can be used to decrease wall thickness in the heat exchanger or to increase the surface area over which the fluid flows. Both of these characteristics increase the effectiveness of a heat exchanger.

The advantage of using additive manufacturing in the creation of heat exchangers is that a complex internal geometry can be produced without requiring complex machining operations. Fused deposition modeling allows parts to be created at the same speed per material volume nearly regardless of the part geometry. This method allows a part with a complex geometry to be created in a cost-effective manner. A complex geometry allows for an increase in the surface area available for heat transfer without increasing the overall volume of the heat exchanger. Another benefit of additive manufacturing is that the manifold used in the heat exchanger can be constructed to reduce the pressure drop in the manifold because the geometry can be optimized for fluid flow as many manufacturing constraints have been lifted. A reduction in the pressure drop across the manifold provides energy savings as it reduces the work required to pump the incoming and outgoing airstream through the manifold. Due to the manufacturing advantages of additive manufacturing, it should be economical to produce counter flow type heat exchangers as seen in figure 2 [3].

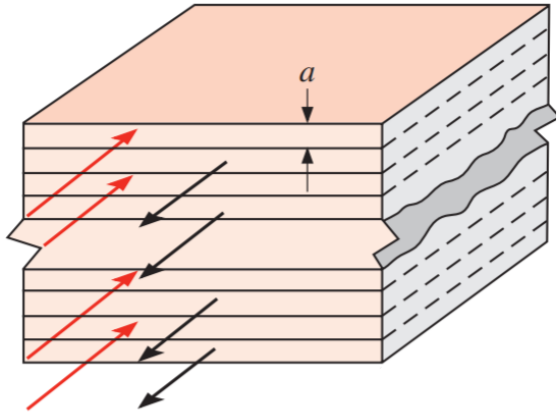

Figure 2: counter flow heat exchanger of the flat plate construction [3].

The counter flow arrangement of the heat exchanger is the type that offers the theoretically offers the highest effectiveness of any heat exchanger arrangement [3]. The ease of constructing a polymer heat exchanger makes it easier to use this arrangement and to offset the drawbacks of the counter flow arrangement such as the increased size as compared to crossflow heat exchangers.

Recently there has been an increase in the variety of materials that can be printed using the fused deposition modeling method. These new materials have created the opportunity to create parts that were not possible before due to the increased range of material properties that are now available. Through the use of composites, the thermal conductivity of polymers has been substantially improved bringing the thermal conductivity of the composite materials to between 2.5W/m-k and 20 W/m-k [6,7]. These polymer composites are composed of a polymer binder and thermally conductive filler such as metal particles or carbon fibers [7]. The thermal conductivity of these composites is mainly due to the filler material providing thermally conductive pathways as the filler material is orders of magnitude more conductive than the thermoplastic binder [2,6]. Increasing the thermal conductivity of polymers eliminates the main drawback of polymers, which is their low thermal conductivity [6,7].

In air to air heat exchanger, the convective resistance is often the dominating factor of the overall resistance in the heat exchanger [6,8]. Due to the convective terms dominating the conductive terms of the overall resistance, the thermal conductivity of the wall of the heat exchanger does not have a large effect on the overall thermal resistance [6,8]. This means that a thermoplastic composite can be substituted for a metallic alloy without having a large impact on the overall thermal performance of the heat exchanger. Recently there has been filament developed for fused deposition modeling that contains thermally conductive materials such as carbon fiber [9]. Readily available commercially manufactured composite filament contains twenty percent by weight carbon fiber. This type of filament allows for the creation of thermally conductive heat exchanger components by fused deposition modeling.

Another advantage of using polymers is that compared to many metals they have good chemical resistance to corrosion [8]. This property is important in a heat recovery ventilation application as higher effectiveness can be obtained by capturing the latent heat from the water that may condense in the heat exchanger [2,7]. The quantity of condensation that forms is a function of the relative humidity in the warmer air stream and the difference in temperature between the warm and cold air stream. This condensation creates an environment that can corrode many metals and therefore necessitates the use of alloys that are resistant to corrosion. The formation of condensation in the heat exchanger does not need to be avoided if polymers are used as they will not be corroded. An important aspect of the chemical properties of the polymers is their flammability, as they will be installed in residential and commercial buildings, they must not be excessively flammable. Due to the large surface area in a heat exchanger, the flammability of the polymers is more important than if they were used to make a solid part. The flammability of thermoplastic composites can be mitigated by adding flame retardants to the mixture of thermoplastic and thermally conductive filler [10].

The advantages of creating heat recovery ventilators with additive manufacturing methods permit the cost of a heat recovery ventilator to be reduced so they are more accessible and will make financial sense to install in residential and commercial buildings. Through the use of fused deposition modeling and thermoplastic-based composites, this method is possible as it addresses the main technical constraints that have been preventing the use of polymers in heat recovery ventilation and adds brings some advantages. The use of a composite material eliminates the issue of excessive thermal resistance due to the wall in the heat exchanger. An advantage of additively manufactured heat exchangers is that the manifold design can be optimized for airflow to reduce pumping costs. Another advantage granted by additive manufacturing is that the surface area to volume ratio of the heat exchanger can be increased, which reduces the footprint of the heat recovery ventilator to improving the ease of installation. These advantages will make the use of additively manufactured thermoplastic composite heat recovery ventilators an attractive option in the future.

Chapter 2

HEAT TRANSFER

There are three basic types of flow arrangements for heat exchangers counter flow, cross-flow, and parallel flow [3]. When a heat exchanger is in the counter flow arrangement the two flows are moving in opposite directions to each other [3]. This configuration is able to obtain the highest effectiveness as the outlet temperature of the fluid that has the lower heat capacity can equal the inlet temperature of the fluid with the higher heat capacity [3]. The cross-flow type of heat exchanger has the two flows perpendicular to each other [3]. An advantage of crossflow heat exchangers is that they can easily be constructed to have a large surface area to volume ratio [3,8]. The parallel flow heat exchanger has the two flows moving in the same direction. If a parallel flow heat exchanger had an infinite surface area, the two fluids would enter at different temperatures and leave at the same temperature which limits the effectiveness of a parallel flow heat exchanger [3]. In this paper, the focus will be on counter flow heat exchangers as they offer the highest potential effectiveness.

The overall heat transfer coefficient of a heat exchanger is a property that defines the amount of heat transfer that will occur given the log mean temperature difference of the two flows. This property is determined by the surface area that is available for heat transfer and the convection coefficients of both fluids, the wall thermal resistance, and the fouling factors for each side of the wall [3]. Given a flow arrangement, increasing the overall heat transfer coefficient will increase the amount of heat that is transferred between the two flow streams. In this paper the effects of fouling will be neglected as the quantity of fouling is nearly independent of material used in the heat exchanger as it is dependent on the service life, fluid velocity, and the fluid [3]. For the case of a heat recovery ventilator, the effects of fouling should be identical in a polymeric or conventional heat exchanger so the thermal resistance of the fouling is excluded from this paper. The formula used to calculate the overall heat transfer coefficient can be seen in Equation 1 [3, 8]. In equation 1,: h is the convection coefficient, A is the area, n_o is the overall surface efficiency, R_o is the thermal resistance of the wall and the subscript 1 or 2 means that the property is evaluated for the respective airstream. The overall heat transfer coefficient equation in equation 1 assumes that all the thermal resistances are in series.

$$UA = \frac{1}{\frac{1}{(n_O hA)_1} + R_w + \frac{1}{(n_O hA)_2}} \qquad [1]$$

The thermal resistance R_w is calculated using equation 2 if the wall is a plane where k_w is the thermal conductivity of the wall, δ is the wall thickness in the direction of heat transfer and A_w is the surface area of the wall [8, 3]. This equation shows that in order to decrease the wall's thermal resistance the thermal conductivity of the material and the area of the wall can be increased or the wall thickness can be decreased [8].

$$R_w = \frac{\delta}{k_w A_w} \qquad [2]$$

The thermal resistance R_w is calculated using equation 3 if the wall is a cylindrical tube where k_w is the thermal conductivity of the wall r_o is the outer radius r_i is the inner radius and L is the tube length [3,8]. The conductive resistance can be decreased by making the inner and outer radii closer together, increasing the thermal conductivity of the wall or increasing the surface area of the tube [8].

$$R_w = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi k_w L} \qquad [3]$$

Section 2.1

FLAT PLATE ANALYSIS:

The relationship between wall resistance in the heat exchanger and the resistance due to convection determines if it is practical to use polymeric materials in the heat exchanger. The relationship between the k value of the wall of the heat exchanger and the overall heat transfer coefficient can be seen in figure 3. The type of heat exchanger that was analyzed in the figure below is a flat plate crossflow heat exchanger that has a surface area of one meter and a wall thickness of 3 millimeters. For figure 3 the heat transfer coefficient was assumed to be the same on each side of the wall, as for a heat recovery ventilator the flow on each side of the wall will be identical except for the air temperature. As the h value increases the k value of the wall material begins to have a larger effect, as the thermal resistance due to convection drops and the thermal resistance due to conduction remains constant.

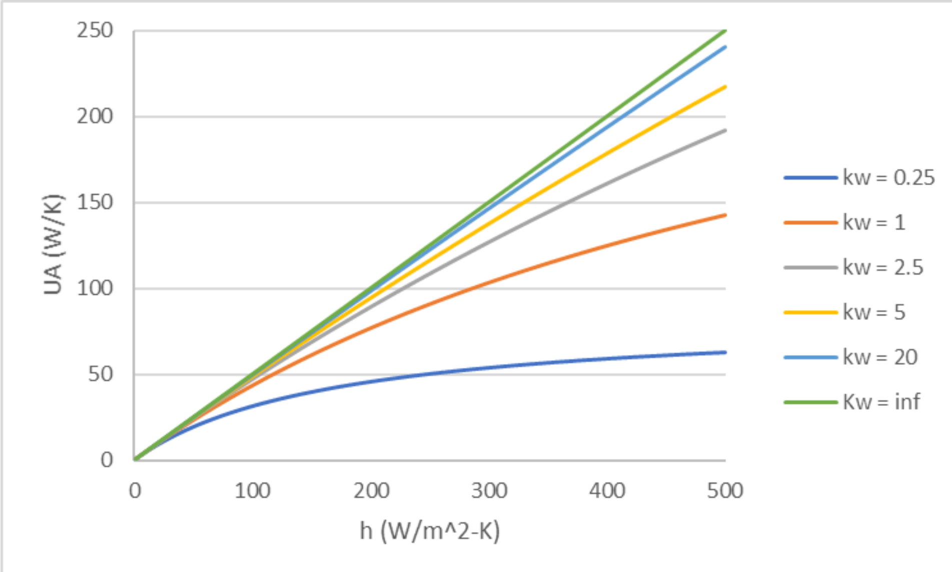

Figure 3: UA vs heat transfer coefficient for a counter flow flat plate heat exchanger for k values ranging from .25(w/m-K) to infinite (w/m-K)

The ratio of wall resistance to convective resistance was calculated using equation 4 where R_w is the wall resistance, R_c is the convection resistance, and h is the heat transfer coefficient on each side of the wall and A is the wall area.

$$\frac{R_w}{R_c} = \frac{R_w}{\frac{1}{(hA)_1} + \frac{1}{(hA)_2}} \quad [4]$$

Equation 4 is simplified to equation 5 when it is assumed that the heat transfer coefficient is equal on each side of the wall and assuming that the heat exchanger is the flat plate type. In equation 5 k_w is the thermal resistance of the wall, A is the wall area, and δ is the wall thickness.

$$\frac{R_w}{R_c} = \frac{\frac{\delta}{k_w A}}{2\left(\frac{1}{h\,A}\right)} \quad [5]$$

The relationship between the convective resistance and the conductive resistance can be seen in figure 4. In figure 4, lines of constant convection coefficient are plotted where the thermal conductivity of the wall varies from 0 to 10 (w/m-K). This plot shows how the thermal conductivity of the wall is more important when the convection coefficient is high but once the thermal conductivity increases to more than 6 (w/m-K), the advantage of further increasing the thermal conductivity quickly diminishes.

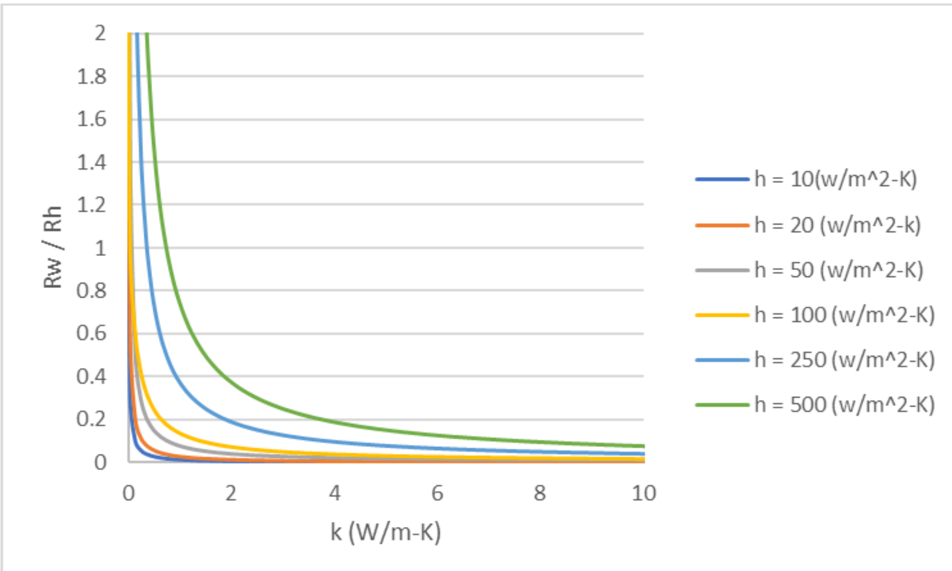

Figure 4: Conductive resistance to convective resistance where the thermal conductivity of the wall varies from 0 to 10 (w/m-K).

This basic calculation of the overall heat transfer coefficient does not include the heat released by water condensing in from the air onto the heat exchanger [2,7,11]. The presence of condensation increases the amount of heat that can be transferred as compared to if dry air at the same inlet temperatures was used in the condenser [2,7,11]. In heat recovery ventilation, latent heat can contribute to as much as 40% of the total heat transfer [2]. The amount of condensation will depend on the humidity of incoming air from whichever air stream is warmer and the temperature difference between the two airstreams. This condensation will change the overall heat transfer coefficient of the heat exchanger as it changes the convection coefficient on the warmer air side [3]. The condensation creates an additional amount of thermal resistance between the wall of the heat exchanger and the airstream, which increases as the thickness of condensation increases [3]. For this analysis it is assumed that the amount of condensation that will form in a polymeric heat recovery ventilator is similar to the amount that will form in a conventional heat recovery ventilator. The type of condensation that will occur is dependent on the material that is in contact with the warmer airstream. If the surface is hydrophobic dropwise, condensation is likely to occur and if the surface is hydrophilic then film condensation is likely to occur [3]. Dropwise condensation has a higher convection coefficient than film condensation and therefore it is preferred when a high rate of heat transfer is desired [3]. Due to the omission of condensation effects from the analysis in this paper, the actual performance of a composite polymer heat recovery ventilator will vary from that calculated in this paper.

Section 2.2

FIN ANALYSIS

The overall heat transfer coefficient can be improved by increasing the surface efficiency as a result of changing the geometry of the wall. The surface efficiency n_o can be improved by changing the surface characteristics of the heat exchanger by adding fins [3]. The formula for surface efficiency can be found in equation 6 where A_f is the fin surface area, A is the total surface area, and n_f is the fin efficiency [3].

$$n_o = 1 - \frac{A_f}{A}(1 - n_f) \qquad [6]$$

The fin efficiency n_f is defined using equation 7 and 8 where t is the plate thickness, h is the convection coefficient, k is the thermal conductivity of the fin, L is the length of the fin, and m is defined in equation 8 [3]. This set of equations are valid for rectangular plate fins where the flow direction is parallel to the fins [3].

$$n_f = \frac{\tanh(m)\,(L+\frac{t}{2}))}{m\left(L+\frac{t}{2}\right)} \quad [7]$$

$$m = \sqrt{\frac{2h}{k \cdot t}} \quad [8]$$

A cross section of a square finned wall can be seen in figure 5, the fluid flow direction is parallel to the fin direction [3].

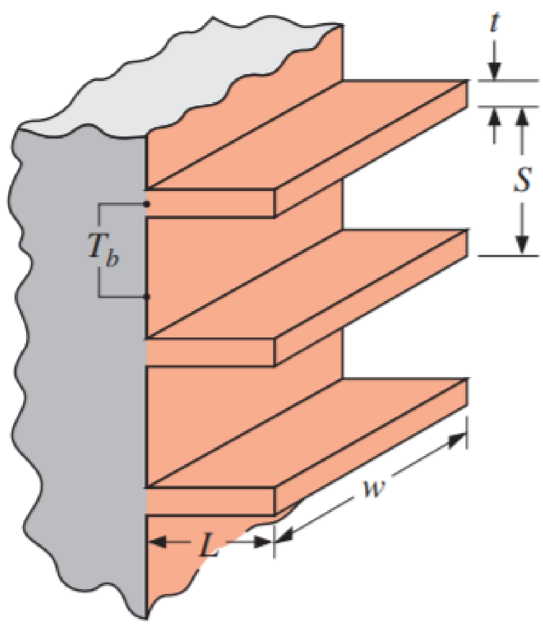

Figure 5: Diagram of a rectangular fined surface where t is the fin thickness, L is the fin length and W is the fin width [3].

The relationship between the fin length and the overall heat transfer coefficient for a range of fin and wall thermal conductivities can be seen in figure 6. In figure 6 the convection coefficient was held constant at 100(W/m^2-K), it was assumed that the fins were identical on each side of the wall, the fins are aligned in the direction of flow, and that the width of the fin was held constant at 1 mm. The thermal conductivity of the wall and the fin was the same because the properties that make a good wall material and fin material are the same, so the materials should be the same especially as it simplifies manufacturing. The fin shape used was a rectangular fin where the fin spacing is equal to the width of the fin. At lower thermal conductivities increasing the length of the fin has a smaller effect on the overall heat transfer coefficient as most of the heat that can be removed is removed around the base of the fin due to the high thermal resistance of the fin itself. At higher thermal conductivities the effect of increasing the length of the fin has a larger effect on the overall heat transfer coefficient as heat is more readily conducted along the length of the fin and this effectively increases the amount of convection that can occur.

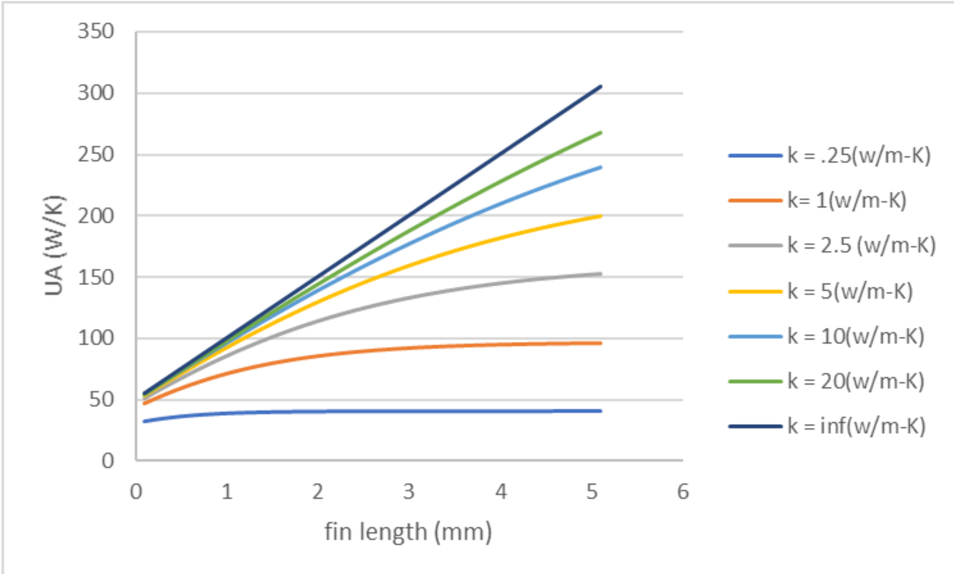

Figure 6: Relationship between fin length and overall heat transfer coefficient for k values ranging from 0.25(w/m-K) to infinite where the convection coefficient is held constant at 200(W/m^2-K).

The relationship between the convective coefficient and the overall heat transfer coefficient of a heat exchanger that fins was plotted in figure 7. The heat exchanger that was modeled has a base area of 1 m^2 and the thermal conductivity of the fins and the wall was held constant at 2.5(w/m-K). The relationship between the overall heat transfer coefficient and the convection coefficient was plotted for fin lengths ranging from 0 to 1 mm in 1 mm increments. Figure 7 shows that the length of the fin has a large effect on the overall heat transfer coefficient when the convection coefficient is small and has a small effect on the overall heat transfer coefficient when the convection coefficient is large. For heat exchanger design this means that the inclusion of fins is more important when the convection coefficient is low and of reduced importance as the convection coefficient increases.

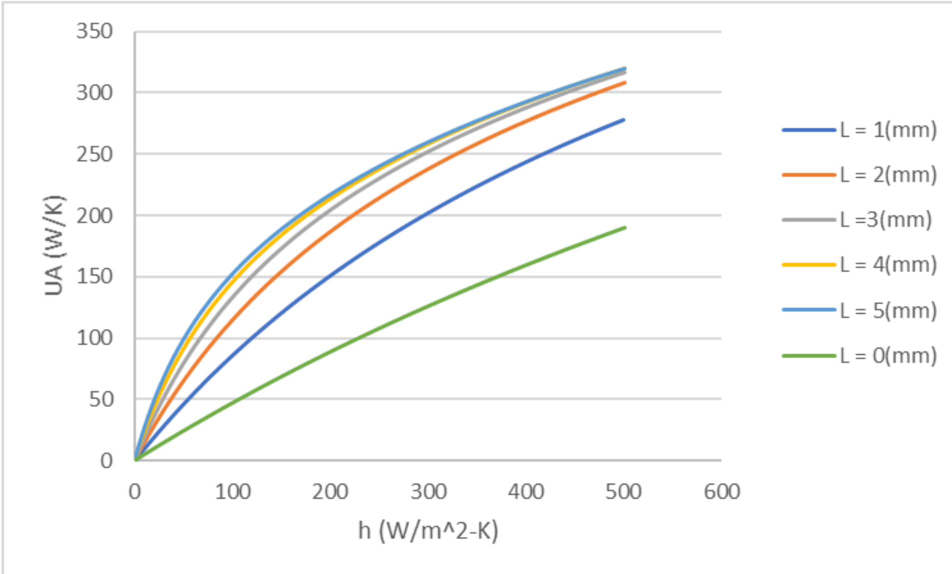

Figure 7: Overall heat transfer coefficient versus convection coefficient for fin lengths ranging from 0 to 5 millimeters and the thermal conductivity of the fin material is 2.5(w/m-K).

The exact size, shape, and spacing of the fins that would be included in a thermoplastic composite heat recovery ventilator depend on several factors. One of these factors is the thermal conductivity of the thermoplastic composite that is available as a higher thermal conductivity increases the effectiveness of fins. Another factor is the convection coefficient of the airflow as a higher convection coefficient reduces the effectiveness of fins, so the use of fins when the convection coefficient is high is less advantageous. The manufacturing constraints also determine if it is cost effective to include fins. This constraint can be mitigated using additive manufacturing but it is not eliminated. The inclusion of fins may also affect the maintenance of the heat exchanger, as depending on the fin configuration it may increase the amount of dust buildup in the heat exchanger and make it harder to clean the heat exchanger. When condensation is present in the heat exchanger, the orientation of the fins becomes more important. The fins, if not properly oriented, can provide a place that condensation can pool and the increased thermal resistance due to the condensate will be detrimental to the overall heat transfer coefficient [3]. This effect can be mitigated by aligning the fins so that the condensate will run off the fins [3]. These factors affect whether or not including fins in a heat recovery ventilator is practical and cost-effective.

Chapter 3

FLUID FLOW

The pressure drop across a heat recovery ventilator is from two sources: the pressure drops in the manifold that supplies air to the heat exchanger and the pressure drop across the heat exchanger itself. It is desirable to reduce the pressure drop across the heat recovery ventilator as the work required to move the air through the heat recovery ventilator is proportional to the pressure drop across the system. The work required to move air across a pressure drop can be seen in equation 9 where $\dot{m}$ is the mass flow rate, g is the acceleration due to gravity, ΔH_{total} is the total head loss across one side of the heat recovery ventilator, and n is the pump efficiency [12]. Equation 9 assumes that the inlet and outlet of each airstream are at the same altitude, the change in kinetic energy is negligible between the inlet and outlet of each airstream and that the mass flow rate remains constant throughout the heat recovery ventilator. To calculate the total work required, the analysis must be done for both air paths in the heat recovery ventilator.

$$Pump\ Work = \frac{\dot{m}\left(\frac{kg}{s}\right) * g\left(\frac{m}{s^2}\right) * \Delta H_{total}}{n} \quad [9]$$

It can be seen that increasing the head loss across the heat recovery ventilator will increase the amount of energy required to run the system.

Section 3.1

HEADLOSS IN THE MANIFOLD

Often the manifold design to a counter flow heat exchanger is composed of a large header that allows the fluid to access alternating gaps between the plates. This type of manifold has a relatively high head loss as it requires the fluid to make a 90-degree turn. These sharp turns in the fluid flow results in a substantial head loss as compared to a more gradual change in the flow direction [12]. Figure 8 shows a common flow path arrangement for a flat plate heat exchanger where it can be seen that the flow has to make an abrupt change in its direction in order to enter the smaller flow paths in the heat exchanger.

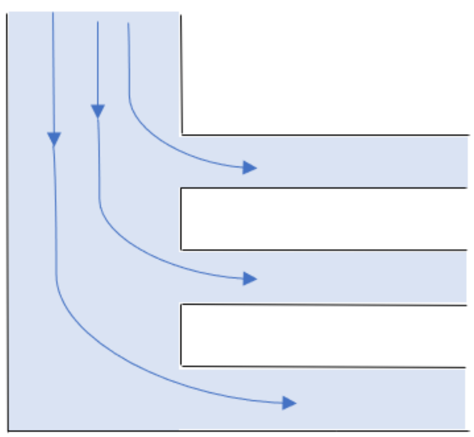

Figure 8: Cross-section diagram of a conventional manifold for a flat plate heat exchanger.

One of the methods used to minimize the pressure drop across the manifold is to use a fractal-based flow pattern for the manifold of the heat recovery ventilator [13]. In a fractal flow manifold, the flow is gradually divided into smaller diameter paths until the desired number of flow paths is obtained [13]. This type of flow path is commonly found in the circulatory systems of mammals and is depicted in figure 9 [13].

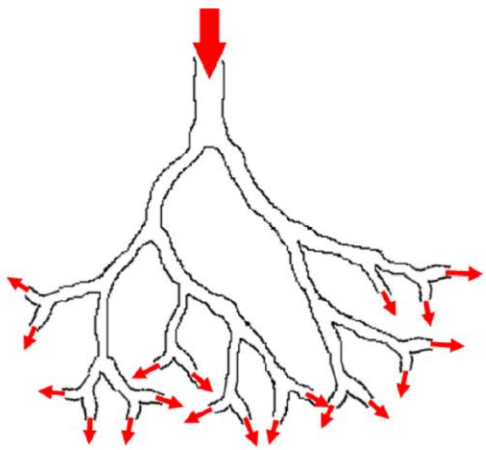

Figure 9: Diagram of a fractal-based flow path that could be adapted for use as a manifold for a heat recovery ventilator [13].

Section 3.2

HEAD LOSS IN THE HEAT EXCHANGER

The head losses in the heat exchanger section of the heat recovery ventilator are related to the flow velocity on the channels of the heat exchanger [13]. In order to create flow conditions that result in a high convection coefficient, the velocity of the fluid can be increased [13]. For turbulent flow, the Nusselt number is dependent on the Prandtl number and the Reynolds number [3]. The only material property that the head loss of the heat exchanger is dependent on is the surface finish as the surface roughness effects the Darcy friction factor [12]. The head loss for an additively manufactured heat exchanger of the same geometry as a conventionally manufactured heat exchanger may be higher due to the surface roughness left from the manufacturing process [5]. The head loss across a heat exchanger can be reduced by reducing the flow velocity, which can be achieved by increasing the area perpendicular to the flow path the flow can pass through [12]. The head loss in an additively manufactured heat exchanger may be higher than one made using conventional methods. The advantage that an additively manufactured heat exchanger has is that the internal geometry can easily be constructed in a way to minimize head loss.

Chapter 4

MATERIALS

The materials that have traditionally been used to construct heat exchangers have primarily been metallic alloys due to their high thermal conductivity and corrosion resistance [2]. Recently polymer composites have been developed that have thermal conductivities that range from 2.5W/m-K to 20W/m-K.[2,6,7] These composites are composed of a polymer matrix and a filler material that has a high thermal conductivity[2,6,7]. The amount that a conductive filler can increase the thermal conductivity of the overall composite can be seen in figure 11 [2]. Figure 11 shows that increasing the thermal conductivity and volume fraction of the filler material will improve the thermal conductivity of the composite [2]. There are diminishing returns when the conductivity of the filler material is increased to many times that of the matrix material [2]. This point of diminishing returns increases as the volume fraction of filler material increases [2].

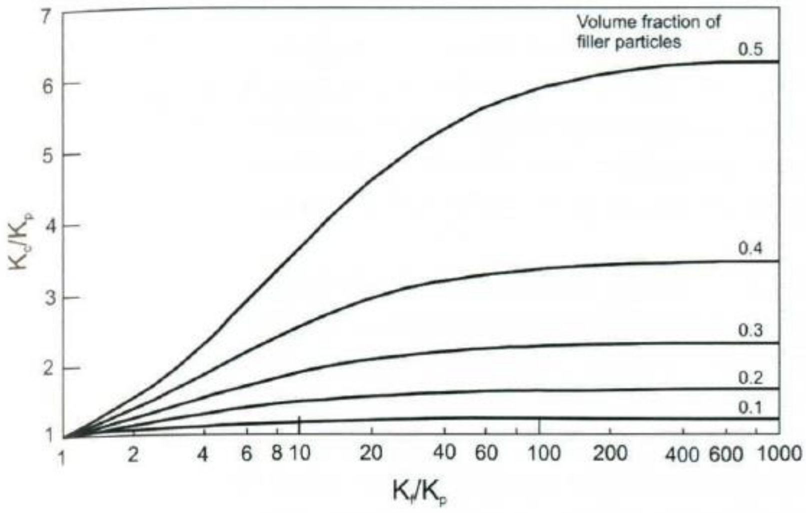

Figure 10: Predicted ratio of thermal conductivity of a composite to the binding material versus ratio of the thermal conductivity of the filler material to the matrix where K_c is the thermal conductivity of the composite, K_p is the thermal conductivity of the matrix, and K_f is the thermal conductivity of the filler material[2].

The shape of the filler material also affects how it contributes to the thermal conductivity of a composite [2]. When the filler material is able to make a continuous path through the matrix, the thermal conductivity of the composite is greatly enhanced [2]. The volume fraction of filler material that is required to form continuous conductive paths is dependent on the shape of the material [2]. In figure 11, the thermal conductivity versus filler concentration for a composite composed of a nylon matrix and a copper filler is plotted [2]. It can be seen that the most effective shape of filler is the fiber and the least effective is the sphere [2]. The effectiveness of fiber is due to the interactions between fibers, as they are the shape that is most likely to contact each other [2]. Another advantage of using a fiber as the filler material is that the inclusion of fiber materials in a thermoplastic matrix increases the tensile strength and impact strength as compared to the thermoplastic matrix [6].

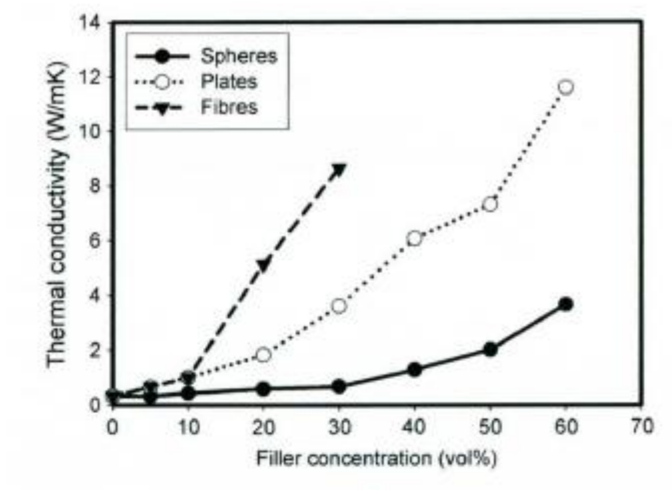

Figure 11: thermal conductivity of a thermoplastic composite versus filler concentration for spherical, plate and fiber filler [2].

The optimal choice for the material used to create an additively manufactured heat recovery ventilator is the material that has a relatively high thermal conductivity, low cost, and can easily be manufactured. There are many commercially available options for thermoplastic-based composites that are already available and meet these requirements [2, 6, 7, 9]. These polymer composites are a good fit for their use in a heat recovery ventilator, as the temperatures that the polymers are exposed to is low enough that there is not a risk of melting or excessive creep [8]. As heat recovery ventilators operate with a low-pressure, difference across the wall of the heat exchanger thus the mechanical properties of the wall material are not of particular importance.

Chapter 5

MANUFACTURING

Additive manufacturing is any manufacturing process that adds material to create a finished part, as opposed to subtractive processes that remove material to achieve the desired part shape [4]. Additive manufacturing allows for the creation of parts that have a complex internal geometry that could not be easily manufactured using traditional methods [5]. This method is useful in the creation of a heat recovery ventilator as parts such as the manifold and heat exchanger that traditionally had to be made of many different parts can now be created as a single unit. The cost to create a structure using additive manufacturing is dependent on the amount of material, used not the shape that is being manufactured [5]. For example, a hollow part is less expensive to produce than a sold one of the same external dimensions [5].

The additive manufacturing method that is focused on in this paper is fused deposition modeling as it is a relatively prevalent additive manufacturing process that creates parts using a thermoplastic filament [4,5]. One of the reasons that fused deposition modeling is prevalent is that there is no chemical post-processing required and the machines are relatively inexpensive as compared to other additive manufacturing methods [5]. Fused deposition modeling works by melting a thermoplastic filament and extruding that filament through a print tip [4,5]. As the plastic is extruded the print tip is moved in one plane once a layer is complete the print head is raised and the next layer of thermoplastic is deposited on top of the previous layer [4,5]. To prevent part warping and to improve the bonding between layers the whole process takes place in a heated environment [4]. A diagram of a fused deposition modeling print head can be seen below in figure 13[4].

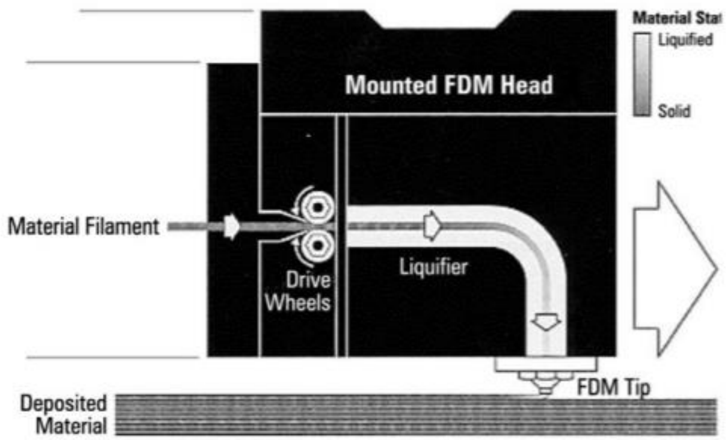

Figure 12: Diagram of a fused deposition modeling print head [4].

There have been filaments developed for fused deposition medaling that contain thermally conductive materials such as carbon fiber [9]. These filaments will allow for the creation of additively manufactured parts that have high thermal conductivities as compared to a thermoplastic part [9].

CHAPTER 6

DISCUSSION

Currently, most residential heat recovery ventilators are constructed using metallic alloys due to their high thermal conductivity and corrosion resistance [2]. As can be seen in the heat transfer analysis section of this paper, the thermal conductivity of the wall material is not of great importance in an air to air heat exchanger due to the relatively low convection coefficients. The effect that the wall thermal conductivity has on the overall heat transfer rate is small once the thermal conductivity of the material is above 2.5 W/m-K. The advantages of increasing the thermal conductivity of the wall quickly diminish once the thermal conductivity of the wall is greater than 5 W/m-K as its performance is about the same as a perfect conductor. Additionally, the importance of the thermal conductivity of the wall material decreases as the wall thickness decreases. Due to the availability of polymer composites that have thermal conductivities that range from 2.5 W/m-K to 20 W/m-K, changing the wall material from a metallic alloy to a thermoplastic composite would not negatively affect the overall heat transfer coefficient [2,6,7]. This makes using a thermoplastic composite for the wall material in a heat exchanger a good choice for a heat recovery ventilator.

The inclusion of fins in a heat exchanger is designed to increase the surface area available for convection to occur thus reducing the convective resistance [3]. As can be seen in the heat transfer analysis section of this paper, the thermal conductivity of the fin material is an important factor in the overall heat transfer coefficient of a heat exchanger that contains fins. The thermal conductivity of the fin becomes increasingly important as the fin length and the convection coefficient increases. The thermal conductivity of thermoplastic composites is large enough that for an air to air heat exchanger, such as that found in a heat recovery ventilator, the implementation of fins can still be effective, especially when the convection coefficient relatively small. As composite polymers are developed that have higher thermal conductivities than those currently available, the practical length of fins will increase. This makes thermoplastic composites a good choice for the fin material of a heat recovery ventilator.

The pressure drop across the manifold in an additively manufactured manifold can be improved as compared to the traditional manifold by using a fractal-based flow path [13]. This type of flow path is not traditionally used in heat recovery ventilators, as creating the required geometry using subtractive manufacturing would be cost prohibitive. The use of a fractal-based flow pattern also has a heat transfer advantage as due to the three-dimensional nature of a fractal flow pattern it makes it easier to implement the counter flow arrangement as compared to the cross-flow method [13]. The counter flow arrangement has a higher potential effectiveness as compared to the cross-flow arrangement [3]. These advantages of a fractal-based flow path make it a good choice for the manifold of an additively manufactured thermoplastic composite heat recovery ventilator.

The head loss inside an additively manufactured heat exchanger will be larger than that of a traditionally manufactured heat exchanger of the same geometry because the surface finish of an additively manufactured part will have more roughness than that of a subtractive manufactured part [5]. The head loss across the heat exchanger can be reduced by reducing the flow velocity [12]. It is possible to reduce the flow velocity by increasing the area that the flow can pass through [12]. There is a trade-off when reducing the velocity of the flow between head loss and the convective heat transfer coefficient, as decreasing the flow velocity decreases both the convective heat transfer coefficient and the head loss [3,12]. There is also a trade-off of heat exchanger size to head loss, as to reduce the head loss and maintain the same overall heat transfer coefficient the area of the heat exchanger must be increased. As the resolution of additive manufacturing improves, the surface roughness of additively manufactured parts will decrease and this, in turn, will reduce the difference in head loss between a traditionally manufactured heat exchanger and an additively manufactured heat exchanger.

Additive manufacturing has the ability to produce parts that have complex internal geometries as compared to subtractive manufacturing [4]. This is important for the creation of the heat exchanger and manifold sections of a heat recovery ventilator as they often are complex parts. The use of additive manufacturing allows the manifold to be almost any shape and this allows for the manifold to be optimized for fluid flow instead of for ease of manufacture, as would be the case of it was made using traditional manufacturing methods. The construction of the heat exchanger section can be greatly simplified as the wall and fins can be produced as one part. A disadvantage of fused deposition modeling is that the material that is used must be in the form of a thermoplastic filament, which limits the range of materials available [4,5]. Fused deposition modeling was chosen as the additive manufacturing method to focus on in this paper, as the machines are relatively inexpensive as compared to other additive manufacturing methods and it has the ability to produce parts that are made of thermoplastic composite materials [5, 9] These factors allow fused deposition modeling to produce parts that have a high thermal conductivity as compared to a pure thermoplastic part [9].

The thermoplastic composite materials were chosen as the focus of this paper due to their increased thermal conductivity as compared to pure thermoplastics while also retaining the ability to be formed using fused deposition modeling [2,6,7,9]. The additional benefits of thermoplastic composites are their ability to survive in a corrosive environment [8]. This resistance to corrosion is important as condensation will form inside of the heat recovery ventilator during its operation [2]. Another advantage of thermoplastic, as compared to metallic heat exchangers, is that for hydrophobic plastic the heat transfer coefficient for condensation is greater than for a hydrophilic surface [3]. This difference is due to condensation occurring dropwise on the hydrophobic surface and film condensation occurring on the hydrophilic surface [3]. The properties of thermoplastic composites are generally advantageous for the application of a heat recovery ventilator.

Chapter 7

CONCLUSION

The properties of thermoplastic composites are compatible with the material requirements of a heat recovery ventilator as they are sufficiently thermally conductive, will not corrode in wet conditions, and have sufficient mechanical strength. These thermoplastic composites are also compatible with the fused deposition modeling process, which allows these materials to be used in an additive manufacturing process. The use of additive manufacturing in the construction of a heat recovery ventilator reduces the geometric constraints that are imposed by manufacturing limitations. The design of the manifold can be optimized to reduce the pumping power required, which will decrease the operational expenses. Due to the reduction of manufacturing constraints, the addition of internal features to increase the rate of heat transfer, such as fins, will not add additional steps to the manufacturing process. This simplification of the manufacturing process will allow composite polymer heat recovery ventilators to be produced in a cost-effective manner. The production of additively manufactured thermoplastic composite heat recovery ventilators is feasible and should be executed.

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