Determination of convective heat transfer coefficient for automated fiber placement (AFP) for thermoplastic composites using hot gas torch

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ABSTRACT
In heat transfer analysis of AFP process using a hot gas torch, the convective heat transfer which occurs between the hot gas flow generated by a torch nozzle and a composite substrate plays an important role in the heat transfer mechanism. In order to model the convective heat transfer, a local heat flux equation \( q_0 = h(DT) \) is utilized where \( q_0 \) is the energy flow per unit of area per unit of time, \( h \) is the convective heat transfer coefficient between the hot gas torch and the composite surface, and \( DT \) accounts for the temperature difference between the two media. This coefficient \( h \) is dependent on various number of parameters such as nozzle geometry and its configuration relative to the surface of the substrate, type and configuration of the roller, gas flow rate, temperature of the gas, type of the gas etc. Researchers on the heat transfer analysis for automated composites manufacturing have used values of \( h \) that vary from 80 W/m²K to 2500 W/m²K. This large range gives rise to uncertainties in the determination of important behavior such as the temperature distributions, residual stresses, and deformations of the composite structures due to the manufacturing process. The reason for these large differences can be due to the differences in the process parameters in each of the studies. The process parameters can include the volume flow rate of the hot gas, the gas temperature, the distance between the nozzle exit and the surface of the composite plate, the angle of the torch with respect to the surface of the substrate etc. In addition, the value of the \( h \) coefficient may not be constant over the heating length of the process. The purpose of this paper is three fold: 1. To investigate the AFP process parameters that may affect \( h \). 2. To investigate different methods for the determination of \( h \), and 3. To develop a procedure for less-time-consuming determination of \( h \) for the purpose of analysis for residual stresses and deformations.

KEYWORDS
Convective heat transfer coefficient; automated fiber placement; thermoplastic composites; impinging jet heat transfer

Introduction
With increasing use of composites in many engineering applications, the need for manufacturing techniques with higher production rates for large scale production in low cost is evident. Traditional processing techniques, such as hand laminating, is

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slow and cannot provide a fast rate of production for new emerging applications. Furthermore, it is based on the skill of technicians and thereby the issue of repeatability in terms of quality and performance of the final composite parts may arise [1–3]. In order to overcome the limitations in traditional manufacturing techniques, the trend is toward the robotic processing of composite structures [4]. Automated Fiber Placement (AFP) offers one of the solutions to traditional processing methods by automating the layup process. Owing to its unique features such as using narrow tapes and having control over steering the fibers, AFP holds many potential benefits which satisfy the demands for high performance structural components [5, 6]. AFP can be used for processing both thermoset and thermoplastic composites; however, due to the numerous advantages of thermoplastics over thermosets such as infinite shelf life, recyclability, low processing time and high fracture toughness, automated manufacturing of thermoplastic composite parts has garnered the attention of different industries in the last decade [1, 7, 8].

The AFP machines are designed for different applications. Depending on the type of material being used (thermoset or thermoplastic), type of the heat source (laser, heat lamp, infrared or hot gas torch) and configuration of the placement head (single or multi tow heads), there are different AFP systems [9]. In the last decade, laser-assisted AFP has garnered attention among different industries particularly in aerospace industry for manufacturing of advanced composite structures [10–12]. Despite the potential benefits from the laser such as faster processing rates, high energy density, more focused and more effective heating, it has some challenges. These include safety issues involved with implementation of laser, difficulty in controlling the precise location of the end of the beam, and the limitation of laser for glass fiber based polymer composites [3]. On the other hand, the hot gas torch (HGT) has been used as the heat source for processing thermoplastic composites for variety of applications [3, 7, 13]. The advantages of implementation of HGT can include but not limited to better heat distribution within the joining area, directly heating the polymer (which is different from the laser which introduces the heat through the fibers), safety of the process, and less challenges in positioning of the torch nozzle [3].

In Figure 1 (Left), the AFP machine at Concordia Center for Composites is illustrated where it is used for manufacturing of thermoplastic composite structures using a HGT. In the thermoplastic fiber placement head as shown in Figure 1 (Right), there is an incoming tape which is the raw material coming from the creel system. It is fed into the head with a controlled amount of tension. The heating system is based on the nitrogen gas which is fed into the back of the torch housing where there are some heating elements to heat up the gas. The hot gas is then delivered to the torch nozzle which is employed to heat up the incoming tape and certain area of the substrate. Eventually, there is a compaction roller which is used to consolidate the material onto the substrate [14–16]. The hot gas coming out of the torch nozzle exit has high temperature up to 1000°C. As such, at the surface of the composite substrate, there is a significant temperature difference between the hot gas flow and the substrate [9]. The heat energy provided by the hot gas torch (HGT) is then transferred into the material via heat convection. In order to model the convective heat
transfer, a local heat flux equation is employed as follows [17, 18]:

$$q'' = h_{HGT}(\Delta T)$$  \hspace{1cm} (1)

Where \( q'' \) (W/m\(^2\)) is the heat flux, \( h_{HGT} \) (W/m\(^2\).K) is the convective heat transfer coefficient between the composite substrate and the HGT and it accounts for the conversion of a portion of the kinetic energy of the gas upon impact with the surface of the composite material; and \( \Delta T \) (K) is the temperature difference between the aforementioned media.

**Literature review on heat transfer analysis for AFP**

In heat transfer analysis of the AFP process using HGT, the convective heat transfer is considered as an external boundary condition in the problem. As such, as the first step to do the analysis, the convective heat transfer coefficient \( (h) \) needs to be known. Several values for the \( h \) coefficient were used by several researchers. In 2004, Tosso et al. [19] used an infrared camera to measure the temperature of both the incoming tape and the substrate in the static position. Then, temperature gradients along two different directions were found from the temperature data. This was then used to estimate the convective heat transfer coefficient. The \( h \) was estimated to be around 80-100 W/m\(^2\).K for both the incoming tape and the substrate. Tierney et al. [20] used the forced jet-impingement theories to obtain the \( h \) coefficient in their heat transfer model developed for tow placement process. Despite the introduction of formulations, no particular value was reported in their study for the \( h \) coefficient. Using the heat transfer coefficient values for impinging jets, Kim et al. [21] assumed the \( h \) coefficient to be 900 W/m\(^2\).K in the vicinity of the nip point and for the incoming tape to be 250 W/m\(^2\).K. A few years later in 2004, the same authors [22] employed the finite element method (FEM) to obtain the distribution of the convection heat transfer coefficient over the composite surface. The flow analysis was conducted for the region between the incoming tape and the composite substrate. Heat transfer coefficient distribution exhibited two peaks within the range of 400-500 W/m\(^2\).K right before the nip point. The values reported, however, were only valid for the test parameters considered in their study. Li et al. [23] in 2015, used birth and death of elements technique in ANSYS to obtain the temperature field during the processing of thermoplastic composites. The \( h \) coefficient values used as an input in their model were within the range of 900-1000 W/m\(^2\).K depending on the nozzle temperature. Sonmez et al. [24] assumed a coefficient of 2500 W/m\(^2\).K in their study to investigate the effect of different process parameters in thermoplastic composite tape placement process on crystallization behavior and consolidation condition of the composite parts.

An experimental method, on the other hand, was used by several researchers to estimate the \( h \) coefficient for the case of AFP. In this method, first a value for convective heat transfer coefficient is assumed. The temperature distribution is measured experimentally using embedded thermocouples. The calculated temperature distribution from thermal analysis models for the similar processing parameters is obtained and compared with experimental results. The \( h \) coefficient is then modified through an iterative process until the predicted numerical temperature results match the experimental temperature values. Using this technique, the \( h \) coefficient was found to be 350 W/m\(^2\).K for the filament winding process [25, 26]. Khan [27] used the same technique for AFP of thermoplastic composites and reported a range of 180-280 W/m\(^2\).K for a variety of gas volumes in his study. In order to determine the convective heat transfer coefficient in their study, temperatures were measured using the embedded K-type thermocouples mounted through the thickness of the already placed carbon fiber/PEEK composite laminate. In order to predict the temperature numerically, a one-dimensional heat transfer model was used to predict the temperature through the thickness of the composite laminate. Having assumed a value for the \( h \) coefficient, through an iterative process, it was modified until the predicted temperature profiles matched well with the experimentally measured temperatures [27]. More recently, in 2019, Tafreshi et al. [28] investigated the temperature distribution due to the moving heat source in AFP of thermoplastic composites. A finite difference (FD) code was generated in MATLAB based on the energy balance approach and the temperature gradient in both lay-up and through-thickness directions were predicted numerically. Unidirectional composite strips were manufactured using AFP and fast-response K-type thermocouples were embedded in various locations through the thickness to determine thermal profiles experimentally. It was shown that \( h = 990 \) W/m\(^2\).K yielded good agreement to match the maximum temperatures measured experimentally with predicted numerical results. This coefficient value was close to the ones reported in literature [21, 23].

**Factors affecting the heat transfer coefficient \( h \)**

In order to understand factors that may affect the value of the heat transfer coefficient \( h \), it is necessary to examine the mechanism for the heat transfer. For the case of AFP using a hot gas torch, the heat transfer is from a hot gas stream impinging on a flat plate. This phenomenon has been extensively studied for the
applications of cooling of hot plates such as turbine blades, hot electronic substrates etc., using cool air (or other type of gas) streams. Even though the heat flow is reverse (from hot plate to cool stream) in these applications, it is reasonable to assume that the coefficient of heat transfer coefficient is applicable for the case of hot gas stream and cooler plate (the case of AFP heating).

Factors affecting the $h$ coefficient in impinging jet over flat plate

Significant amount of work has been done on the heat transfer between hot plates and cool impinging fluid stream [29–38]. Impinging jets are widely used for heating and/or cooling of large surface areas where high local heat transfer is required [29–31]. In this method, a single or array of nozzles of different geometries are used to impinge air or another type of gas upon the surface of interest to induce high local heat transfer rates [32, 33]. The heat transfer mechanism involved in this method is forced convection in which an external means (impinging jet or torch nozzle) is utilized to create temperature gradients [17, 18]. Schematics of the impinging flow and its characteristic regions are illustrated in Figure 2. Figure 2a shows the case where the torch is perpendicular to the plate surface, and Figure 2b shows the case where the torch is inclined at an angle $\theta$. One particular feature of the flow in the case of impinging jet is the occurrence of the stagnation flow point. This refers to the location where the velocity of the gas stream is 0. For the case of perpendicular stream, the stagnation flow point is at the intersection between the jet stream and the plate surface. For the case of inclined stream, the stagnation flow point is displaced from the intersection between the jet stream and the plate. The amount of the displacement depends on the particular flow situation.

Reynolds number

For the case of heat transfer involving the impinging jet over a flat surface, the Reynolds number ($Re$) has strong influence. $Re$ is defined as the ratio of inertia to viscous forces [18]. In the HGT, Reynolds number can be calculated as [19]:

$$Re = \frac{VT \cdot D}{vT} \quad (2)$$

Where $D$ is the inside diameter of the torch nozzle (m), $VT$ is the temperature dependent flow velocity at the torch nozzle exit (m/s), and $vT$ is the temperature dependent kinematic viscosity of the gas (m$^2$/s). Knowing the torch nozzle cross-sectional area ($A$) and the volumetric flow rate of gas at high temperature ($Q_T$), the temperature dependent flow velocity $VT$ can be calculated as following [19]:

$$VT = \frac{QT}{A} \quad (3)$$

Where $QT = \frac{\rho_T}{\rho_T} Q_{RT}$. Having the gas density at high temperature $\rho_T$ (kg/m$^3$) and at room temperature $\rho_{RT}$ (kg/m$^3$) along with the volumetric flow rate of the gas at room temperature $Q_{RT}$ (m$^3$/s), $VT$ and thus $Re$ can be calculated from equations (3) and (2) respectively. Thermophysical properties of nitrogen gas at higher temperatures can be obtained by interpolating the available data in [18].

Nusselt numbers

The $h$ coefficient is determined via Nusselt number (Nu):

$$h = \frac{Nu \cdot k}{D} \quad (4)$$

Where $D$ is the characteristic length (equal to nozzle diameter in this case) and $k$ is the thermal conductivity of the hot gas.

Effect of $Re$ number, $L/D$, $r/D$ and $\theta$ on $Nu$

The Nu number depends on the $Re$ number, the distance between the nozzle exit and the surface L, the nozzle diameter D, the inclined angle $\theta$, and the position $r$ on the surface of the plate.

The dependence of Nu on Re numbers, and on the distance between the nozzle and the substrate depends on the intervals for Re and for H/D. There can be
different relations for different intervals of Re numbers, and different intervals of H/D. For example, from reference [35], for $H/D \leq 1$, for the case of perpendicular stream, for the range of Re numbers $3700 \leq Re \leq 30,000$, the Nu at the stagnation flow point is obtained from the measured data to be:

$$Nuo = 0.726Re^{0.53}(H/D)^{-0.191}$$ (5)

Equation (5) represent data with average and maximum error of 5 and 21% respectively.

For the case of nozzle-plate spacings less than $H/D \leq 0.5$, the correlation becomes:

$$Nuo = 0.663Re^{0.53}(H/D)^{-0.248}$$ (6)

with slightly better accuracy. In equations (5) and (6) the subscript "o" indicates that the Nu values are at the stagnation point.

The dependence of the Nu number on the position on the surface of the substrate (represented by $r/D$ where $r$ is the radial position from the stagnation point), can be illustrated by the curves in Figure 3 (reproduced from reference [35]). It can be seen that Nu varies significantly along the $r$ direction. The value of Nu can vary from 550 to 20 (a ratio of 27.5) for only two values of Re numbers of 5100 and 23,000.

The above examples (equations 5, 6 and Figure 3) are for the case of perpendicular stream, where $L = H$ in Figure 2a. There is also the effect of the inclined angle $\theta$, as shown in Figure 2b. It can be seen from Figure 2b that the inclined angle $\theta$ has strong effect on the position of the stagnation point. As such the distribution of Nu number, and thus $h$, along the surface of the substrate will be shifted, as compared to the case of perpendicular stream.

**Averaging Nu over a length**

Examining the literature on the work on heat transfer in impinging jet shows that the Nu number depends on a lot of parameters, most of the results are experimental, and most equations are derived from the treatment of experimental data. As shown in Figure 3, there is significant variation of the Nu with respect to the position $r$ on the surface of the substrate. As such, there is a tendency to average the Nu over a certain length. Besides, in the heat transfer analysis to determine the temperature distribution in the composite substrate during AFP processing, the heat input is over a certain length, and usually the $h$ value is assumed constant over this length. As such, using the $h$ value that is averaged over a certain length is appropriate. Lytle et al. [35] shows that the average Nusselt numbers evaluated over $r/D = 1.0$ and $r/D = 2.0$, for the range of nozzle-plate spacings $0.1 \leq H/D \leq 1.0$, and Reynolds number range of $3600 \leq Re \leq 27,600$ are given as:

![Figure 3. Dependence of Nu on r/D (reproduced with permission from Elsevier, reference [35], perpendicular stream).](image)
The impinging jet study for heat transfer coefficient in AFP

The impinging jet over a flat plate studies have been mainly for the heat transfer between a hot plate and a cool stream of fluid (air). Even though for the case of AFP, a hot stream and a cool plate is the situation, it is reasonable to assume that the heat transfer coefficient between the two cases are the same, except opposite in sign. In addition, in AFP, there are many obstructions to the jet stream before the stream hits the surface of the substrate (such as rollers and incoming tape). In order to get the two types of heat transfer to be as close together as possible, so that some comparison can be made, the obstructions need to be removed. Here the h value where the roller is removed is called \( h_{\text{AFP-free}} \), and the h value where there is a roller is called \( h_{\text{AFP-roller}} \). Figure 4 shows the arrangement without the roller (left), and with the roller (right).

The comparison with the h value obtained from impinging jet \( (h_{\text{IMP}}) \) is done using the set up for the AFP process without any roller (free jet). The comparison between \( h_{\text{IMP}} \) and \( h_{\text{AFP-free}} \) is reasonable only if the Reynolds number and the H/D distances of the two cases are within the same intervals. The relevant parameters for the case of the AFP machine at Concordia Center for Composites are shown in Table 1.

From the parameters in Table 1, the range of Re numbers is 5360 \( \leq \text{Re} \leq 6314 \), and the range of H/D is 0.42 \( \leq \text{H/D} \leq 1.67 \). These parameters fit the window of applicability for equations (7) and (8) given above (From reference [35], equations (9) and (10) are valid within the Re range of 3,600 \( < \text{Re} < 27,600 \) and the range of H/D of 0.1 \( < \text{H/D} < 1.0 \)). Although the upper limit of H/D for the AFP machine at Concordia is 1.67 (as compared to the recommended value of 1.0), Marin [33] proposed to use a correction factor. Using the approach of Martin, the correction factor is very small and is negligible. As such, comparison between \( h_{\text{IMP}} \) and \( h_{\text{AFP-free}} \) is reasonable.

Replacing the Re using the expressions in equations (2) and (3), equations (7) and (8) can be written as:

\[
\frac{\text{Nu}_{r/D=1.0}}{D} = 0.424 \text{Re}^{0.57} (H/D)^{-0.33}
\]

(7)

\[
\frac{\text{Nu}_{r/D=2.0}}{D} = 0.150 \text{Re}^{0.67} (H/D)^{-0.36}
\]

(8)

Where \( Q_{T} \) is the gas flow rate, and \( \nu_{T} \) is the gas kinetic viscosity at temperature T.

For the work to determine the h value using the AFP approach (shown below), the heating length is taken to be 10 mm \( (r/D = 5/6) \), which falls outside the range between \( r/D = 1 \) and \( r/D = 2 \). The Nu number for the heating length of 10 mm is obtained by extrapolation between the values obtained using equations (9) and (10). This value will be denoted as average coefficient \( h_{\text{IMP}(10\text{mm})} \), as:

\[
h_{\text{IMP}(10\text{mm})} = \frac{\text{Nu}_{(10\text{mm})} k}{D}
\]

(11)

Additional factors influencing the h value (due to AFP set up with roller)

For the real, practical AFP set up (with roller), there are additional parameters that will affect the h value. These include the presence of the roller, the presence of the incoming tape, and the heat loss to the environment. The roller may be made of different types of materials, of different dimensions. The distance between the nozzle exit and the roller may also vary. The impinging jet experiments may have been performed with a chamber with controlled environment, whereas in the case of AFP, the
surrounding air environment may not be well controlled. There can be two approaches to address this issue. One is to quantify the thermal characteristics of all these components, and to incorporate them into the heat transfer analysis (which is very involved). The other approach is to lump all these parameters into a single quantity called the heat loss to the environment. For this second approach, a different procedure (from the impinging jet approach) is used to determine the heat transfer coefficient $h$ (denoted as $h_{\text{AFP-roller}}$).

The $h_{\text{AFP-roller}}$ only determines the amount of energy that is absorbed by the substrate. The difference between $h_{\text{IMP-ave}}$ and $h_{\text{AFP-roller}}$ may be considered to represent the heat loss. This procedure is shown below.

**Determination of the heat transfer coefficient for AFP - $h_{\text{AFP-roller}}$**

A different approach to determine the coefficient of heat transfer is proposed. Rather than focusing on the delivery of the energy (as in Impinging jet), this procedure focuses only on the energy that is absorbed by the substrate. This method can obtain the coefficient of heat transfer for the case of the free jet (without roller) and for the case with roller. The method is similar to the one used in literature by various authors [19, 25–28]. In this method, two different sets of work are carried out.

The first set of work involves experimental measurement of the temperature at certain locations within the composite substrate during the AFP process (free jet or with roller). The second set of work involves the finite difference determination of the temperature at the same location as in the experiment. For the finite difference calculations, first a value for the $h$ coefficient is assumed. This $h$ value is assumed to be constant over the heating length for the AFP process. The maximum temperature results from both numerical and experimental methods are compared. The $h$ coefficient is then updated and through an iterative process, the best value for $h$ is found in the numerical model to match the maximum numerical temperature with the maximum experimental temperature. This process is repeated for many process parameters (such as free jet and with roller) to determine the $h$ coefficient between the hot gas torch and the composite substrate. Figure 5 shows a flow chart to explain the steps used in this procedure. In order to determine the $h$ coefficient through an iterative process, a scanning algorithm is coded in MATLAB to perform the analysis. In this algorithm, a function is defined in which the $h$ coefficient is an input and the numerical maximum temperature at the location of the thermocouple is selected as an output. An error percentage is defined as the difference between the numerical and experimental maximum temperatures. The error percentage is monitored continuously for different values of the $h$ coefficient and the best value for $h$ is found in the numerical model corresponding to the minimum error percentage.

The heat transfer model used in the methodology presented for determination of the $h$ coefficient is essentially the same as the one presented by authors in [28]. In this model, based on the energy balance approach, finite difference formulation of the moving heat source problem in AFP of thermoplastic composites was derived and coded. Numerical results from a moving heat source traveling across the upper side of a composite substrate were obtained and $h$ coefficient was calculated. It was shown that using this method,
the numerical model was able to capture the maximum temperature and overall trend of temperature variation in different layers with good agreement with experimental results [28].

In order to compare the $h$ values obtained from the different methods, experiments were performed using the AFP machine at the Concordia Center for Composites for the different parameters, as follows.

**Experimental setup**

AFP work cell and Aluminum paddle tool at Concordia Centre for Composites as shown in Figure 1 (Left) are used to perform the experimental trials. Fully impregnated AS4/APC-2 carbon fiber/PEEK tapes supplied by Solvay are used as the prepreg material in the setup [39]. In the heating system, nitrogen gas is used to provide heat to the material. Nitrogen as an inert gas helps to protect the prepregs from oxidation [6]. Figure 6 depicts the experimental setup used. Unidirectional composite strips of 508 mm (20 inch) long making up 10 layers are manufactured first under nominal processing parameters (nozzle temperature 875 °C, nitrogen gas flow rate 75 SLPM, compaction pressure 80 lb (356 Newton)). The laminate is allowed to cool down to reach room temperature to achieve thermal equilibrium. Subsequently, on the upper side layer, a fast-response K-type thermocouple (Omega CHAL-002; response time 0.08 s) is mounted using a Kapton® tape. Because of Kapton tape’s good insulating and temperature characteristics, it is used to protect the wires as shown in Figure 6 (left). After the installation of the thermocouple, the last layer is deposited. When the Nip point of the consolidation roller arrives on top of the thermocouple, it deposits the last composite layer, and the thermocouple becomes embedded into the composite substrate. Figure 6 (right), depicts the AFP head while placing the last composite layer over the embedded thermocouple.

The nozzle temperature is changed by changing the power input into the electrical heater in the torch housing and the nitrogen gas flow rate is changed by changing the input into the nitrogen line supplying the nitrogen on the back of the torch housing. For each case, the heat source moves from one end to the other end of the composite strip with speed of 25.4 mm/s (1 in/s) without material deposition and the temperature signal is recorded by the thermocouple, which is embedded into the composite substrate, underneath one layer of composite material. After completing one pass, the setup is allowed to cool down to reach room temperature. The complete lay up of the composite, the tool, and the location of the embedded thermocouple along with the thermal measurement apparatus are shown schematically in Figure 7. The thermocouple is connected to a connector, and the temperature is measured by Data Acquisition system (DAQ) at 100 Hz. A personal computer is used at the end to display information and store the thermal data during the process.

**Design of experiments**

The purpose to carry out the experiments is to correlate between $h_{IMP}$, $h_{AFP}$ (free jet), and $h_{AFP}$ (with roller), for the particular set of the AFP machine at Concordia. A range of parameters are used. The torch nozzle temperature is set in the range of 600 °C – 900 °C (note that the nozzle temperature indicates the temperature of the gas exiting the
nozzle and it is measured by a thermocouple located at the tip exit of the nozzle) and the nitrogen gas flow rate is selected in the range of 50 – 90 SLPM. Both parameters can be adjusted using the AFP operator interface. For each case (in total 36 cases), the process is repeated five times to ensure readings are repeatable and the data are consistent. As such, in total 180 runs (36/C2 × 5) are performed.

The parameters involved include the distance between the nozzle and the roller (denoted by ‘A’ in Figure 8), the distance between the nozzle and the substrate (denoted by ‘H’ in Figure 8) and the angle of the torch with respect to the substrate. The consolidation roller used in this study is made out of stainless steel with the width of 0.5 inches and the diameter of 0.5 inches. As for the nozzle to substrate spacing H, three different distances of 2.5, 5 and 10 mm (0.098, 0.197, 0.394 inches respectively) are selected to perform the experimental trials. The design of experiment and the values assigned for each case are summarized in Table 3. In total, 36 cases are considered.

Properties of nitrogen at different temperatures are shown in Table 2. The design of experiments is as shown in the first 3 columns in Table 3.

### Results and discussion

The h values from Table 3 are plotted in Figure 9 (for H = 2.5 mm), Figure 10 (for H = 5.0 mm) and Figure 11 (for H = 10.0 mm). In each graph, there are 3 groups of curves for the flow rates of 50 SLPM, 70 SLPM and 90 SLPM. The following observations can be made:

**Effect of temperature**

Increasing the torch temperature would increase the value of \(h\). This applies for all nozzle-substrate distances and flow rates. The relationships are approximately linear.

**Effect of flow rates**

Increasing the flow rate would increase the value of \(h\). This applies to all torch temperatures and nozzle-substrate distances. However, the effect of the flow rate is more on \(h_{\text{IMP-ave}}\) and this effect becomes less for \(h_{\text{AFP-free}}\) and even less for \(h_{\text{AFP-roller}}\). In fact, for \(h_{\text{AFP-roller}}\) at \(H = 10.0\) mm and 900 °C (Figure 11), the effect becomes negligible.

**Effect of nozzle-substrate spacings**

Figure 12 shows the effect of nozzle-substrate spacings on values of \(h\). The larger is the value of the
| T (°C) | Q (L/min) | H (mm) | Reynolds (Re) | Nuave (D1) | Nuave (D2) | Nuave (10 mm) | h_{IMP,Q=0} (W/m²K) | h_{IMPave} (W/m²K) | h_{AFPfree} (W/m²K) | h_{AFProller} (W/m²K) | K_Cfree | K_Croller |
|-------|-----------|--------|---------------|-------------|-------------|---------------|----------------|----------------|----------------|----------------|------------|------------|
| 600   | 50        | 2.5    | 536.341       | 81.31       | 75.62       | 64.82         | 77.42          | 792            | 754            | 615            | 515        | 0.815      | 0.683      |
| 70    | 2.5       | 790.878| 97.19         | 91.60       | 81.21       | 93.34         | 94.7           | 910            | 697            | 547            | 576        | 0.766      | 0.601      |
| 90    | 2.5       | 965.41 | 111.03        | 105.71      | 96.10       | 107.31        | 1082           | 1046           | 768            | 572            | 574        | 0.734      | 0.547      |
| 700   | 50        | 502.12 | 78.59         | 72.89       | 62.08       | 74.69         | 831            | 790            | 656            | 557            | 630        | 0.830      | 0.705      |
| 900   | 50        | 474.22 | 76.22         | 70.54       | 59.73       | 72.34         | 872            | 828            | 708            | 621            | 654        | 0.855      | 0.750      |
| 800   | 50        | 101.90 | 94.00         | 81.07       | 71.72       | 82.63         | 994            | 874            | 845            | 754            | 815        | 0.744      | 0.562      |
| 90    | 2.5       | 905.42 | 107.31        | 101.90      | 92.04       | 103.55        | 1135           | 1095           | 815            | 615            | 874        | 0.555      | 0.405      |
| 70    | 2.5       | 666.11 | 91.10         | 85.45       | 74.83       | 87.22         | 913            | 796            | 649            | 527            | 650        | 0.381      | 0.123      |
| 900   | 50        | 450.85 | 74.16         | 68.49       | 57.69       | 70.28         | 805            | 838            | 771            | 673            | 769        | 0.650      | 0.418      |
| 70    | 2.5       | 631.09 | 88.64         | 82.96       | 72.28       | 84.74         | 1038           | 1050           | 870            | 703            | 828        | 0.399      | 0.152      |
| 900   | 50        | 114.13 | 101.26        | 95.74       | 85.54       | 97.44         | 1255           | 1207           | 945            | 727            | 783        | 0.593      | 0.487      |
| 70    | 2.5       | 88.71  | 77.71         | 70.17       | 66.65       | 77.75         | 1099           | 963            | 541            | 423            | 562        | 0.350      | 0.124      |
spacing, the lower is the $h$ value. The relations are nonlinear.

Relations between different $h$ values

- From Figures 9–11, there is the relationship $h_{\text{IMP-ave}} > h_{\text{AFP-free}} > h_{\text{AFP-roller}}$ for any set of process parameters. This is to be expected. However, there are significant differences between $h_{\text{IMP-ave}}$ and $h_{\text{AFP-roller}}$, indicating that there is only a small amount of the delivered energy is absorbed by the substrate.
- It can be of practical use if some relation between $h_{\text{IMP-ave}}$ and $h_{\text{AFP-roller}}$ can be established. This is because $h_{\text{IMP-ave}}$ may be obtained from the literature on impinging jet heat transfer, while $h_{\text{AFP-roller}}$ relates to the real AFP process. The determination of $h_{\text{AFP-roller}}$ involves the measurement of the temperature close to the

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**Figure 9.** Variation of $h$ values with nozzle temperature at $H = 2.5$ mm. [Dotted line ($h_{\text{IMP-ave}}$) - Dashed line ($h_{\text{AFP-free}}$) - Broken line ($h_{\text{AFP-roller}}$)].

**Figure 10.** Variation of $h$ values with nozzle temperature at $H = 5.0$ mm. [Dotted line ($h_{\text{IMP-ave}}$) - Dashed line ($h_{\text{AFP-free}}$) - Broken line ($h_{\text{AFP-roller}}$)].
surface of a substrate plus numerical calculations and iterations to determine the temperature based on some assumed initial $h$ values. This process is time consuming and costly. If some relation exists between $h_{\text{IMP-ave}}$ and $h_{\text{AFP-roller}}$, such as a conversion ratio defined by:

$$K_c = \frac{h_{\text{AFP-roller}}}{h_{\text{IMP-ave}}}$$  \hspace{1cm} (12)$$

then one may obtain $h_{\text{IMP-ave}}$ from the literature and multiply it with $K_c$ to obtain $h_{\text{AFP-roller}}$. For the particular set up of the AFP machine at Concordia, the $K_c$ values are shown in Table 3.

**Recommended procedure for the determination of $h_{\text{AFP-roller}}$**

From the knowledge and experience of the above described work, the developed procedure for the determination of the $h_{\text{AFP-roller}}$ for any particular AFP machine process parameters, is summarized as follows:

**Figure 11.** Variation of $h$ values with nozzle temperature at $H = 10.0 \text{ mm}$. [Dotted line ($h_{\text{IMP-ave}}$) - Dashed line ($h_{\text{AFP-free}}$) - Broken line ($h_{\text{AFP-roller}}$)].

**Figure 12.** Variation of $h$ with nozzle to substrate spacing.
Procedure 1:
This long procedure consists of two sets of work. One is to place thermocouples at different locations close to the top of the substrate to determine the maximum temperature during the process. The other set of work involves carrying out numerical method such as finite difference. This is used to determine the temperature distribution, starting with an initial assumed $h$ value. Iterations are made until the maximum temperatures obtained from both techniques match. This procedure takes into account the real aspects of the set up for the process. The final determined value is denoted as $h_{\text{AFP-roller}}$. This can be time consuming and costly.

Procedure 2:
This consists of the following steps:

- From the machine parameters such as those shown in Table 1, determine the range of Reynolds numbers and the range of $H/D$ distances.
- Consult the literature for work on Impinging Jet heat transfer. Look for data for process parameters that fit the range of Re numbers and $H/D$ distances.
- If suitable data exist, determine the average $h$ values ($h_{\text{IMP-ave}}$), similar to equations (9) and (10).
- The $h$ value is averaged over the heating length used in the process.
- Obtain the conversion ration $K_c$ as shown in equation (12).

Usefulness of the procedures:
When one varies the torch temperature and the flow rate, the $h_{\text{IMP-ave}}$ can be obtained using equations similar to equations (9) and (10). The $h_{\text{AFP-roller}}$ can be obtained by multiplying $K_c$ with the $h_{\text{IMP-ave}}$ (i.e. without having to repeat procedure 1) for the new torch temperature and flow rate.

Illustrative example:
The use of the above procedures is illustrated in the following example. Figure 13 shows the steps.

- Process parameters are: $T = 600^\circ C$, flow rate 50 SLPM, $H = 2.5$ mm.
- For the impinging jet procedure: At $600^\circ C$, consult Table 2 to get $\rho_T = 0.306 \, \text{kg/m}^3$, $k = 0.0504 \, \text{W/m.K}$, $\nu_T = 95 \times 10^{-6} \, \text{m}^2/\text{sec}$. From these, using equations (2) and (3), Reynolds number is calculated to be 5363.4, and Nusselt number is calculated to be 77.42, using equation (4).
- Using equation (9) and (10) and extrapolate for a length of 10 mm, $h_{\text{IMP-ave}} = 754 \, \text{W/m}^2\text{K}$
- Use a conversion coefficient from Table 2 of 81.5%, one obtains: $h_{\text{AFP-free}} = 615 \, \text{W/m}^2\text{K}$

Conclusion
Procedures for the determination of the convective heat transfer coefficients $h$ for the automated fiber placement of thermoplastic composites using a hot gas torch are proposed. The procedures consist of two aspects. First is the semi-numerical-experimental aspect which involves the measurement of temperatures at thermocouples embedded within composite substrates during the AFP process, in combination with finite difference determination of these temperatures using iteration of initially assumed $h$ values. Second is the impinging jet aspect involves the calculation of $h$ coefficient based on Nusselt number and Reynolds number during the flow of the hot gas stream from the nozzle to the composite substrate. By correlating the $h$ values obtained from the impinging jet aspect to values obtained from the semi-numerical-experimental aspect, a relatively simple procedure is derived for the determination of the $h$ values for the AFP process. For future work, experimental measurement of the $h_{\text{AFP-roller}}$ for different roller configuration can be useful to establish an inventory of $h_{\text{AFP-roller}}$ values.
Disclosure statement

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