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Investigation of heat transfer in trocar system for minimal invasive surgery

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Abstract: Laparoscopic surgery has transformed surgical procedures with its minimally invasive approach, involving small incisions and quicker patient recovery. Surgeons use different techniques to access deep tissues within the body. One common step in laparoscopic surgery is the insertion of a trocar system through one of these incisions. This allows for the introduction of instruments and the insufflation of the abdominal cavity with heated carbon dioxide to maintain a suitable operating environment. Here, we report a parametric study investigating the behaviour of different materials utilised in trocars in response to thermal exposure. The results obtained indicate that polycarbonate, acrylic, polyetherimide and polysulfone are favourable materials based on small CO₂ temperature difference between inlet and outlet of the trocar due to heat loss to surrounding medium. They have a high thermal resistance with reduced heat loss from the CO₂ flowing inside the trocar to the atmospheric air. The study provides insights for appropriate selection of materials for a trocar system.

Keywords: minimal invasive surgery; MIS; trocar; fluid flow; heat transfer.

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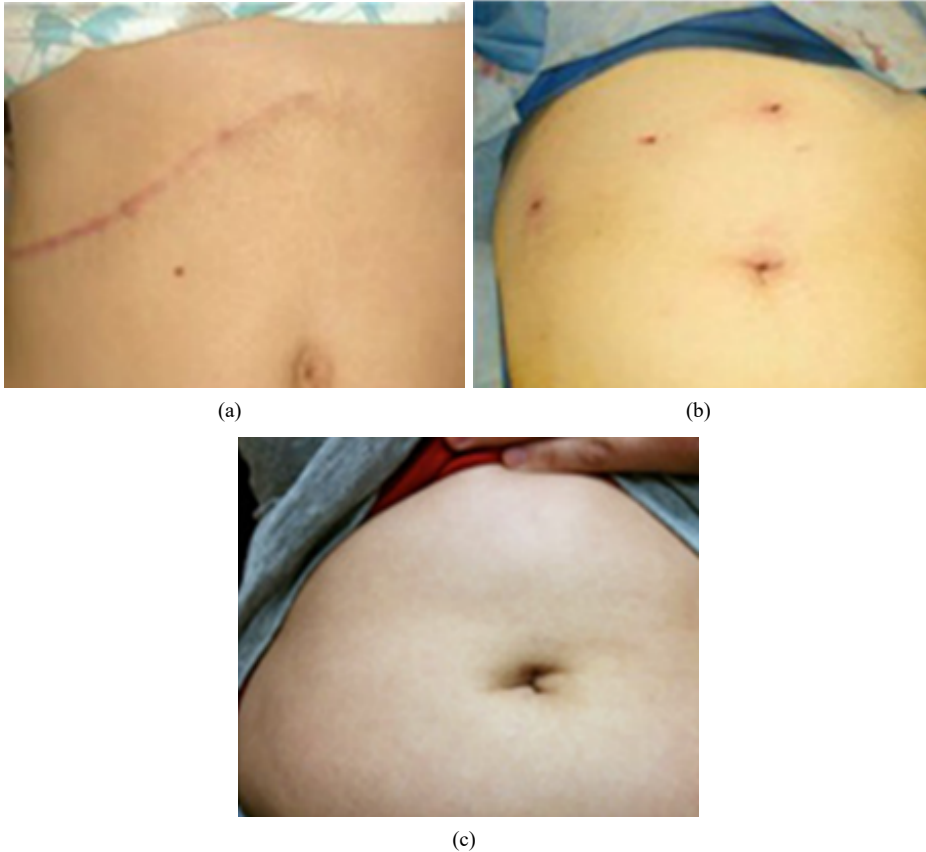
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1 Introduction

Laparoscopic surgery, often known as minimally invasive surgery (MIS), is a procedure in which operations are performed through small incisions using laparoscope, a thin flexible tube equipped with a light and camera to view an internal organ and guide the procedure. MIS offers several advantages compared to conventional open surgery, including smaller incisions, reduced blood loss, shorter hospital stay, faster recovery, lower infection rates, and improved cosmetic results (Bonjer, 2017). Cholecystectomy is an example of a surgery that can be performed as a laparoscopic surgery. Traditionally, laparoscopic cholecystectomy involved several incisions and developed later to a less

invasive surgery implying only one incision (Rudiman, 2021). Figure 1 shows the visibility of the scars after different types of cholecystectomy procedures.

Figure 1 Performing a laparoscopic cholecystectomy, (a) scars after an open cholecystectomy (b) scars after a laparoscopic cholecystectomy with multiple incisions (c) scars after a laparoscopic cholecystectomy with single incision (see online version for colours)



Source: Erbella (2011)

Working instruments are introduced into the abdomen by the surgeon through a system, trocar, that serves as a link between the tools and the patient organ. A trocar is a part within the assembly that is introduced through a cannula. Figure 2 shows the two mentioned parts of the system. Different types of trocar tips are available. The tip can be penetrated through the parietal wall for initial placement of the system with different forces. Plastic or metal cannulas are usually used in the assembly. Depending on the instrument to be used, different sizes and diameters of trocars and cannulas are chosen. All the cannulas have valve mechanism at the top.

Figure 2 Trocar and cannula of the trocar system (see online version for colours)

Source: ChinaOrg (2012)

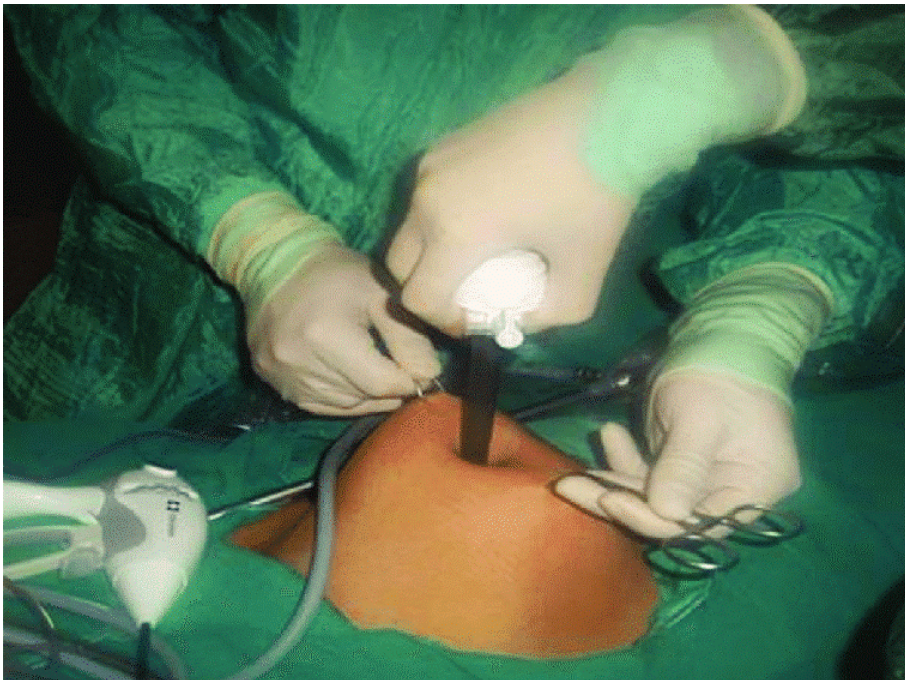
Figure 3 Insertion of Veress needle (see online version for colours)

Source: Mishra (2011)

Small abdominal incisions are made as part of a minimally invasive operation; the number and size of these incisions depend on the ailment that the surgeon is trying to detect or rule out. Typically, 3 to 4 incisions between 1 and 2 cm in length are made (Healthline, 2018). Once the incisions are done, pneumoperitoneum with CO₂ gas can be achieved by either open or closed methods (Datey et al., 2021). The closed method includes the insertion of the Veress needle blindly into the abdominal cavity

as shown in Figure 3. This procedure is then completed by using one of the different tests which determines the proper needle placement. These tests include aspiration, injection, hanging drop and other tests. Each test is done through a specific procedure to ensure that the needle is in the peritoneal cavity. The other method of insertion is the direct trocar insertion, shown in Figure 4. After that, the CO₂ gas is connected to proceed with insufflation. When the Veress needle method is used, the trocar is typically inserted after the insufflation with CO₂. It passes through the umbilicus or another minor abdominal wall incision, and the valve has to be closed to stop CO₂ gas from escaping. Anterior abdominal wall lifting is performed during abdominal entry to avoid damage to intestines or main vessels (Usta et al., 2017). This is assumed to prevent vital organ injuries by creating an adequate distance prior to entry into the peritoneal cavity. As a result, the surgeon can operate and scan the area more easily.

Figure 4 Direct insertion of trocar (see online version for colours)



Source: Usta et al. (2017)

Several works have investigated various aspects of trocars systems. Some of them examined the dynamic changes in friction for various trocars at different instrument velocities (Van den Dobbelsteen et al., 2007). A flexible needle made from a super elastic titanium alloy demonstrated that it is possible for a 26 and 30 mm needle to pass through a 3.5 and 5 mm trocar resulting in less trauma and improved cosmetic effect (Delibegovic, 2022). Moreover, integration of sensory systems into trocars to provide feedback in robotic surgery was presented (Fontanelli et al., 2020), and deep learning models with an alarm system algorithm were employed for safe insertion of trocar (Jearanai et al., 2023).

Here, a new aspect addressing heat transfer in trocar systems is investigated. The prolonged exposure of the trocar material to heated CO₂ during an operation may lead to its deformation due to the thermal stress it is subjected to. The objective of this research is to forecast and examine the behaviour and thermal characteristics of a set of materials utilised in the manufacturing of optical trocars (Ismail et al., 2016). The thermal study considers heat exposure due to the continuous insufflation during surgery and examining the resultant heat distribution in the trocar system for different materials.

The remainder of this paper is organised as follows: Section 2 describes the research methodology. Section 3 reports and discusses the results, followed by the conclusions and recommendations in Section 4.

2 Methodology

The adopted methodology consists of two parts:

- 1 an analytical model describing the relevant equations governing the behaviour of the internal fluid flow through the trocar as well as the resulting heat transfer
- 2 a numerical model developed in COMSOL to simulate the velocity and temperature distribution in the trocar.

2.1 Analytical model

This section presents the analytical model for heat transfer in trocar systems. Particularly, different materials are used to determine the temperature distribution of the CO₂ (fluid) flowing inside the trocar due to the heat loss with the ambient system. The temperature distribution may be predicted by determining the fluid flow type inside the trocar. The first part of this model consists of determining the fluid flow type to select the appropriate correlation of the velocity profile of the fluid. The second part deals with the heat transfer between the fluid flow inside the trocar and the ambient system (room air flow). The variation of the material affects the heat loss from the inside to the outside of the trocar based on its thermal conductivity.

2.1.1 Fluid flow in the trocar

The fluid flow in a trocar is manifested by two types of flow: laminar and turbulent. The laminar flow is characterised by highly ordered motion, while the turbulent flow is described by extremely disordered motion of the fluid particles (Janna, 2020). The type of the flow may be determined by calculating the non-dimensional Reynolds number which is defined as the ratio of inertial forces to viscous forces within the fluid flow. At high Reynolds numbers, the inertial forces, which are related to fluid density and the square of fluid velocity, are significant in comparison to the viscous forces, and hence the viscous forces cannot prevent the fluid from fluctuating randomly and rapidly. However, at low or moderate Reynolds numbers, viscous forces are strong enough to suppress these variations and keep the fluid in line.

In an internal flow (in a trocar), the flow is considered laminar when the Reynolds number is less than 2,300. However, it is a turbulent flow at a Reynolds number

greater than 3000. Moreover, it is assumed to transition between the mentioned values (2,300 and 3,000). The Reynolds number depends on the channel geometry and the thermodynamics properties of the fluid. It can be calculated using the following equation (White, 2011):

$$Re = \frac{\rho \times V \times D_h}{\mu} \quad (1)$$

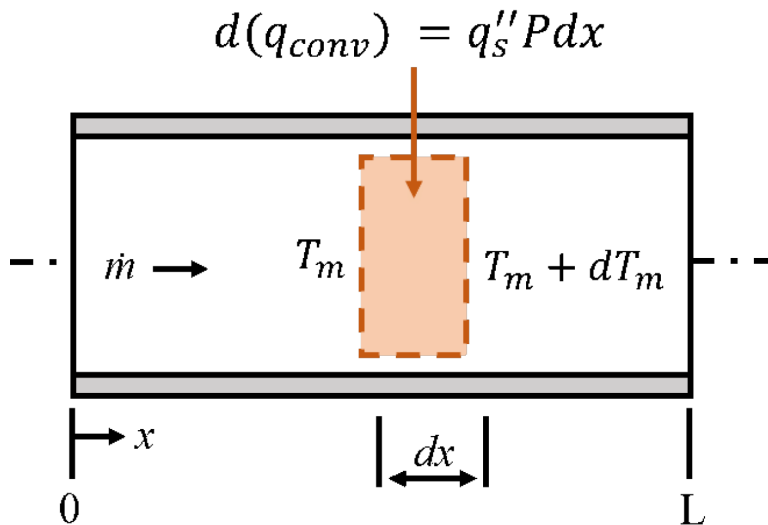
where ρ is the fluid density in kg/m^3 , V is the fluid velocity in m/s , μ is the dynamic fluid viscosity in kg/(m.s) and D_h is the hydraulic diameter of the trocar that may be found by:

$$D_h = \frac{4 \times A}{P} \quad (2)$$

where A is the cross-sectional area (m^2) and P is the perimeter (m) of the channel.

The profile of velocity within the trocar depends on the type of the flow which is either laminar or turbulent flow. Consider a uniformly moving fluid entering a circular trocar as shown in Figure 5. The velocity of the fluid particles in the layer in contact with the trocar's surface tends to zero due to the roughness of the trocar and to the no-slip condition. This layer also causes the fluid particles in the adjacent layers to gradually slow down due to friction. The velocity boundary layer is the region of the flow where the effects of viscous shearing forces induced by fluid viscosity are felt. The thickness of this boundary layer increases in the flow direction (Çengel and Cimbala, 2006).

Figure 5 The differential area used to perform the energy equation (see online version for colours)



The flow in the entrance region is referred to as hydrodynamically changing flow since this is where the velocity profile develops. Beyond this region is the hydrodynamically

fully developed region where the velocity profile is fully established and remains unchanged.

The flow becomes fully developed when the trocar is sufficiently long relative to the entry length, rendering entrance effects negligible. In fully developed laminar flow, each fluid particle moves at a constant axial velocity along a streamline, and the velocity profile $u(r)$ remains constant in the flow direction. Since there is no motion in the radial direction, the velocity component in the direction normal to flow remains unchanged everywhere. The flow, being continuous and completely developed, experiences no acceleration. The velocity profile in a laminar flow is governed by the following equation having a parabolic shape:

$$u(r) = u_{\max} \left(1 - \left(\frac{r}{R} \right)^2 \right) \quad (3)$$

where R is the trocar radius, $u_{\max}$ is the maximal velocity or the center line velocity. Since the velocity component is in the axial direction of the trocar, the profile of velocity may be expressed as function of the average velocity. The average velocity ($u_{\max}$) is defined as the summation of the particle velocities over the cross-sectional area of the trocar as follows (Štigler, 2014):

$$u_{\text{av}} = \frac{1}{A} \int_A u(r) dA = 2 \times u_{\max} \quad (4)$$

where A is the cross-sectional area of the trocar.

Turbulent flow is characterised by the random and rapid variations of swirling areas of fluid, known as eddies, occurring throughout the flow. These variations provide an additional mechanism for the transmission of momentum and energy. The power law velocity profile is a well-recognised representation of the turbulent velocity profile. The power law velocity profile is mathematically stated as follows (Munson et al., 2005):

$$u(r) = u_{\max} \left(1 - \frac{r}{R} \right)^{\frac{1}{n}} \quad (5)$$

The value of $n = 7$ is deemed appropriate for several realistic flow approximations (Munson et al., 2005).

2.1.2 Heat transfer

Heat transfer is a fundamental concept, occurring whenever there is a temperature difference in a medium or between media. This phenomenon is commonly known as a mode of heat transfer. In the first mode, when a temperature gradient exists in a stationary medium, whether it is a solid or a fluid, the term ‘conduction’ is employed to describe the heat transfer across the medium. The concept of thermal conductivity is crucial for conduction, representing the substance’s ability to conduct heat from one side to the other. A lower thermal conductivity signifies enhanced heat insulation and preservation capabilities of the material (Moran et al., 2010).

The second mode of heat transfer is convection. Convection is a process of heat transfer between a surface and a moving fluid when they have different temperatures. This heat transfer can be classified based on how the fluid moves. Forced convection

occurs when external forces, like fans, pumps, or atmospheric winds, make the fluid flow. On the other hand, natural convection, or free convection, happens when the fluid moves spontaneously. As the fluid warms, it becomes lighter and rises, creating a flow. This movement is driven by buoyancy forces, which result from density variations caused by temperature differences in the fluid. Mixed convection occurs when both forced and free convection are at play, combining external forces and the fluid's inherent movement (Moran et al., 2010).

The third mode of heat transfer is thermal radiation. Surfaces at finite temperatures emit energy in the form of electromagnetic waves. Therefore, in the absence of an intervening medium, there is a net heat transfer by radiation between two surfaces at different temperatures (Moran et al., 2010).

The trocar system consists of a cylinder where CO₂ flows inside and the ambient air flows eternally at the surface of the trocar. There are three modes of heat transfer associated within the trocar: the convection associated with the CO₂, by conduction through the thickness of the trocar, and by convection between the external surface of the trocar and the ambient air flow. The heat is transferred by convection between two mediums where at least one is in motion, whereas heat is transferred by conduction through a stationary medium such as solid bodies.

The temperature of the CO₂ along the trocar is determined by considering the thermal resistance between the CO₂ and the ambient air flowing outside the trocar.

The total heat transfer from the CO₂ depends on the mass flow rate of the fluid ($\dot{m}$), the specific heat at constant pressure (C_p) and the difference of temperature between the inlet and the outlet of the trocar. The heat transfer mode in this case is by convection since it is between the internal surface of the trocar and the CO₂ flow. It may be expressed as follows:

$$\dot{Q}_{\text{conv}} = \dot{m}C_p(T_{\text{in}} - T_{\text{out}}) \quad (6)$$

where $\dot{Q}_{\text{conv}}$ is the convective heat transfer rate in W, $\dot{m}$ is the mass flow rate in kg/s, C_p is the specific heat capacity at constant pressure in J/kgK, T_{out} is the outlet temperature of CO₂ in K and T_{in} is the inlet temperature in K of CO₂.

The temperature distribution within the trocar may be calculated by applying the energy balance on a differential element as depicted in Figure 5. The differential form of this equation will be as follows:

$$d(q_{\text{conv}}) = \dot{m}C_p((T_m + dT_m) - T_m) = q_s'' \times P \times dx \quad (7)$$

where T_m represents the mean temperature in the cross section, dT_m is the variation of the mean temperature between the inlet and the outlet of the cross section, P is the surface perimeter and q_s'' is the heat flux at the outside surface of the trocar.

The heat transfer between the air flowing in the room and the surface of the trocar is done by convection. The heat flux is expressed as follows:

$$q_s'' = h(T_s - T_{\infty}) \quad (8)$$

where h is the convection coefficient in the room in W/m²K, T_s is the outer surface temperature of the trocar in K and T_{∞} is the air temperature, in K, flowing in the room.

Equation (7) may be cast in a convenient form by expressing the rate of convection heat transfer to the differential element as dq_{conv} . By substituting equation (8) into (7), the differential temperature with respect to x may be expressed as follows:

$$\frac{dT_m}{dx} = \frac{P}{\dot{m}C_p} h(T_\infty - T_m) \quad (9)$$

By integrating equation (9) and applying the boundary conditions along the trocar (from 0 to the length of the trocar), the temperature distribution may be found and expressed as follows:

$$\int_{\Delta T_m}^{\Delta T_0} \frac{d(\Delta T)}{\Delta T} = -\frac{P}{\dot{m}C_p} \int_0^L h dx \quad (10)$$

$$\frac{\Delta T_0}{\Delta T_i} = \exp\left(-\frac{PLh}{\dot{m}C_p}\right) \quad (11)$$

$$T(x) = -\frac{PxU_t}{\dot{m}C_p} \times (T_\infty - T_i) + T_\infty \quad (12)$$

where U_t is the overall heat transfer coefficient in $\text{W/m}^2\text{K}$, P is the trocar perimeter ($2\pi r$) in m. $T(x)$ is the temperature, in K, at the center of the tube as function of x , x is the position a long length in m, $\dot{m}$ is the mass flow rate in kg/s, C_p is the specific heat at constant pressure in J/kgK , T_∞ is the room temperature in K and T_i is the inlet fluid temperature in K.

The overall heat transfer coefficient is the inverse of the total resistance between two nodes.

$$U = \frac{1}{R_t} \quad (13)$$

The thermal resistance by convection (R_{conv}) and conduction (R_{cond}) in a cylindrical coordinate may be expressed as follows respectively:

$$R_{\text{conv}} = \frac{1}{2 \times \pi \times r_1 \times L \times h} \quad (14)$$

$$R_{\text{cond}} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \times \pi \times L \times k} \quad (15)$$

where h is the convective heat transfer coefficient in $\text{W/m}^2\text{K}$, r_1 is the inner radius of trocar in m, L is the length in m, r_2 is the inner radius of trocar in m and k is the material thermal conductivity in W/mK .

The convection coefficient is calculated by selecting the appropriate correlation of the Nusslet number based on the type of the flow, either laminar or turbulent, and the boundary conditions.

In case of laminar flow with a uniform wall temperature, the following equation is used:

$$Nu = \frac{h \times D}{K} = 3.66 \quad (16)$$

In case of laminar flow with a uniform heat flux, the following equation is used:

$$Nu = \frac{h \times D}{K} = 4.36 \quad (17)$$

In case of turbulent flow, the following equation is used:

$$Nu = \frac{h \times D}{K} = 0.023Re^{4/5}Pr^{0.3} \quad (18)$$

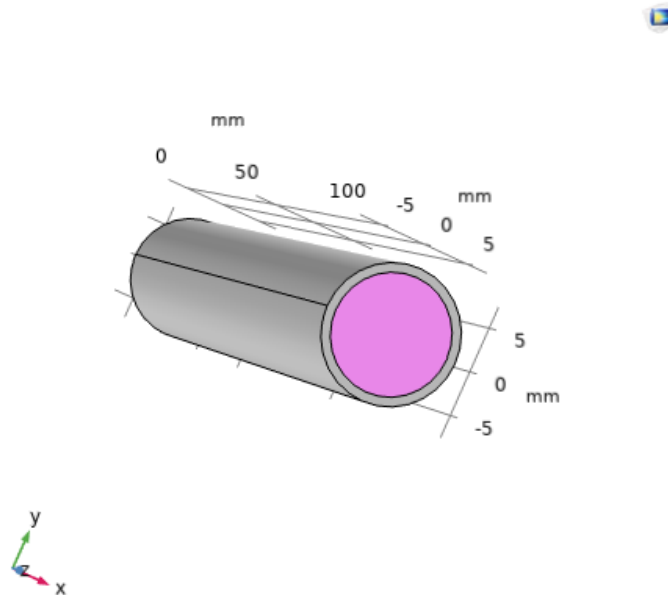
where Nu is the Nusselt number, h is the convective heat transfer coefficient in W/m^2K , D is the trocar diameter in m, K is gas conductivity in W/mK and Pr is the Prandtl number.

2.2 Numerical model

2.2.1 Trocar three-dimensional model

The trocar is modelled based on the characteristics of the commercial trocar system from XNY Medical, a manufacturer and distributor of minimal invasive surgery (MIS) medical devices, China. It is a detailed three-dimensional structure consisting of different parts. Since this approach targets the study of the behaviour of different materials which are mainly affected by the fluid flow through the trocar, many unnecessary elements were neglected when constructing the model. The fluid flow domain was preserved in a manner consistent with the dimensions provided by XNY. Primarily, the diameter through which the fluid flows (13 mm), the height of the tube (103 mm), and the thickness of the material (1 mm) were maintained.

Figure 6 Trocar model (see online version for colours)



The numerical model went through the following steps. First, the geometry of the trocar was built using the model builder module followed by setting the physics of the model

covering heat transfer in laminar flow. Materials were then assigned to the inner pipe fluid, CO₂, and the outer layer constituting the trocar structure as depicted in Figure 6. Furthermore, the boundary conditions pertaining to inlet temperature and initial volume flow rate were set as per the real surgery conditions. Finally, the trocar model was meshed to conduct the desired simulations and obtain the results related to fluid velocity and the temperature distribution.

2.2.2 Trocar material

In the trocar system simulation, CO₂ material was assigned to the fluid domain to model the flow of carbon dioxide gas. The trocar sleeve domain utilised the ‘material sweep’ feature in COMSOL, which enables the switching or modification of assigned material (acrylic, polycarbonate, polysulfone and polyetherimide) within the simulation model. This feature facilitates the exploration of various materials and their impacts on the simulation results.

2.2.3 Physics and study

Different physics interfaces were simulated using a stationary study in COMSOL.

A significant aspect that generates heat during a laparoscopic surgery is the CO₂ flow. To assess the characteristics of this flow, the initial step taken was to generate a suitable flow through the modelled geometry. Laminar flow was specifically considered after evaluating the Reynolds number using equation (1). The volumetric flow rate of the CO₂ is assumed to be 2 L/min. Using the fluid properties of the CO₂, the Reynolds number (Re) was calculated and found to be 393.11 indicating that viscous forces prevail over inertial forces and result in laminar flow.

In the subsequent stage, the flow domain for laminar flow was determined, and specific surfaces were chosen as the inlet and outlet boundaries. Mass flow rate boundary condition was applied at the inlet and a pressure boundary condition at the outlet which was set to 12 mmHg.

In this research, the utilisation of heat transfer analysis in COMSOL is employed to investigate the distribution of heat through the system providing a comprehensive understanding of thermal behaviour. Since the geometric system in this study consists of two domains, namely the solid and fluid domains, the ‘heat transfer in solids and fluids’ physics module provided by COMSOL was utilised. The solid domain was assigned to the trocar sleeve while the fluid domain was given to the CO₂ flow.

For the aim of heat transfer simulation, the initial temperature of the system was set to room temperature (293 K). An inflow boundary with an upstream temperature of 310 K and an outflow boundary were specified at the CO₂ inlet and outlet boundaries, respectively. External natural convection was applied to the outer surface of the trocar, assuming an external temperature of 293 K (room temperature). The study is divided into two parts:

- 1 The trocar is treated as a pipe where the CO₂ flows inside and a heat loss into the room temperature occurs along its entire length.
- 2 In actual condition, the trocar is half inserted into the patient’s body and only the first part is subjected to the free convection in the room. In this case the boundary

condition will be modified where a constant temperature (310 K) will be applied to the outer surface of the part inserted into the body.

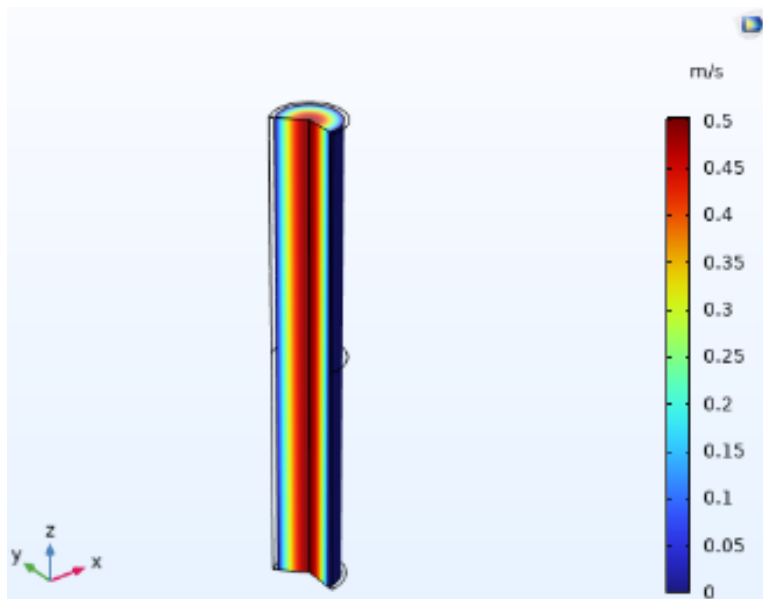
Non-isothermal flow was utilised, which couples laminar flow with heat transfer.

A predefined mesh by the software was utilised. The system comprises two distinct domains, each serving different purposes. With an emphasis on material behaviour, the mesh in the material domain was designated to be refined enhancing accuracy. The flow domain also employed a fine predefined mesh.

3 Results and discussion

The comparison of the material components is performed manually using the equations listed in the analytical model provided in the previous section and compared to the results obtained through COMSOL.

Figure 7 3D velocity profile (see online version for colours)



3.1 Fluid flow validation

In laminar flow, the study is carried on the fully developed region. As shown in Figure 7, the velocity profile remains unchanged after entry length where the fluid became fully developed. In order to find the fully developed region, the simulation of the fluid flow was performed. Figure 8 shows the variation of the fluid velocity with the trocar length. The velocity increases from zero due to the non-slip condition to the maximum velocity (0.5 m/s) at the centerline of the trocar. This variation is shown in this figure when plotting the velocity profile at different positions at the inlet of the trocar. The velocity demonstrates a parabolic profile which corresponds to the

profile described in equation (3). In addition, the velocity profile was plotted at different positions from the inlet of the trocar (20 mm, 40 mm, 60 mm, 80 mm, 90 mm, and 100 mm) in order to determine the position where the flow is considered fully developed.

Figure 8 Velocity profile at different positions in the trocar (see online version for colours)

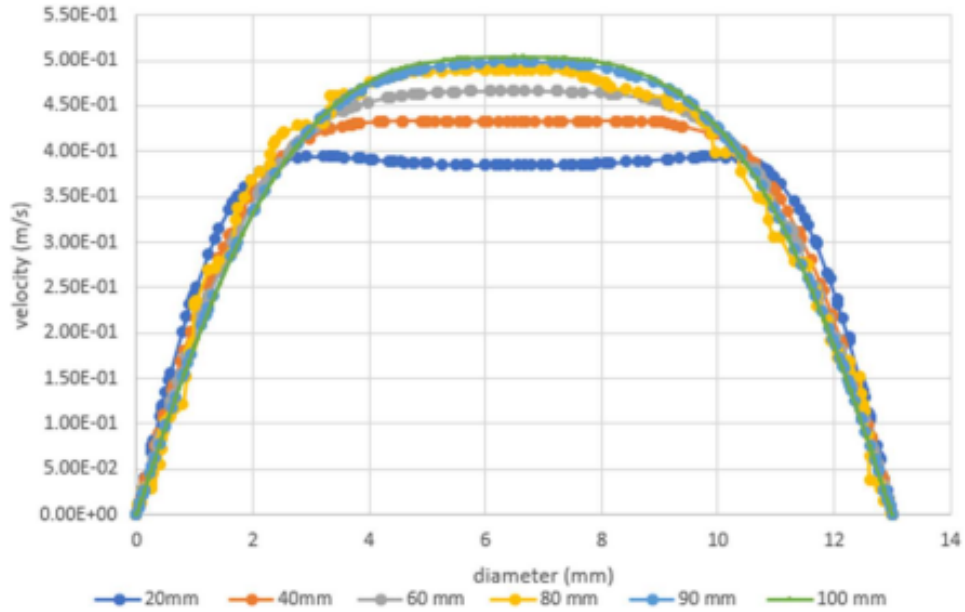
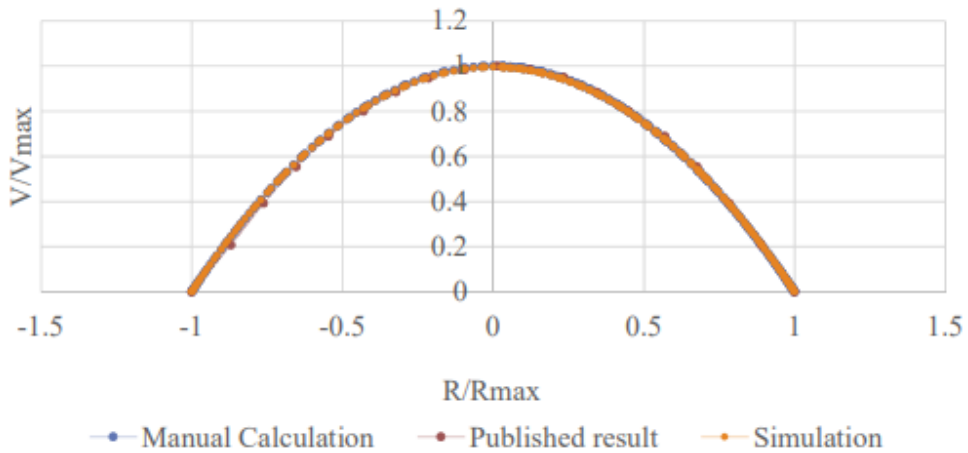


Figure 9 Comparison of the non-dimensional velocities with respect to the non-dimensional radius (see online version for colours)



It is clear that the velocity profile becomes constant after the position 90 mm and the flow is becoming fully developed. The velocity increases from zero near the boundary of the trocar to the maximum value of 0.5 m/s at the centerline of the trocar.

In order to validate the model built in COMSOL, a comparison with the theoretical model expressed by equation (3) and results obtained from the literature was conducted

(Selvam and Thiru, 2014). The comparison was performed using the non-dimensional values of the velocity ($u_r/u_{\max}$) and the radius of the trocar (r/R) where u_r is the radial velocity of the fluid, $u_{\max}$ is the maximum velocity of the fluid at the centerline, r is the radial position and R is the radius of the trocar. Figure 9 shows the comparison of the non-dimensional velocities obtained using equation (3), the simulation, and results found in the literature. The figure shows that the three profiles fit perfectly and the model used in the simulation is validated. The velocity increases from zero at the boundary of the trocar to the unit at its centerline.

3.2 Heat transfer validation

The theoretical dimensionless temperature distribution with respect to the dimensionless radius was compared with the results reported (Pasha et al., 2017) which considers a steady, laminar, and incompressible internal water flow through a pipe, having a constant wall heat flux. The dimensionless temperature in this comparison is determined by ratio of the difference between the fluid's temperature and the surface temperature to the difference between the CO₂ mean temperature and the surface temperature, $\frac{T_w - T}{T_w - T_m}$. As illustrated in Figure 10, both cases show a very close and matching behaviour. Moreover, the maximum dimensionless temperature corresponds to the maximum temperature of CO₂ located at the center of the pipe. In addition, the dimensionless temperature decreases to the minimum value located at the surface of the pipe. This decrease is related to the heat loss to the surrounding by convection and conduction. This comparison revealed that the analytical model is validated and may be used to validate the simulation model.

By investigating the fully developed laminar flow region which has a constant Nusselt number, the CO₂ convective heat transfer coefficient was found to be 5.7 W/m²K using equation (17). The convective coefficient of the free convection in the room was assumed to be 1.85 W/m²K (Incropera et al., 2005). The total thermal resistance consists of convection inside the trocar, conduction through the thickness of the trocar and natural convection outside the trocar. The thermal resistances are calculated using equations (14) and (15). The thermal resistances are added in series and the total thermal resistance is the summation of the three thermal resistances. The overall heat transfer coefficient is evaluated using equation (13) and the temperature distribution may be found using equation (12). The first step in this study involves validating the COMSOL model through a comparison with the calculated results. The second step consists of a comparative study encompassing variation of the temperature distribution due to changing the trocar material.

Polycarbonate is used as material for the trocar in this study. Figure 11 illustrates the temperature distribution of CO₂ in the trocar, showcasing results from both simulation and manual calculations. The temperature of the CO₂ decreases from 310 K at the inlet of the trocar to 309 K at the outlet using the two methods. The decrease of the temperature is attributed to the heat loss from the CO₂ having an inlet temperature of 310 K and the air flow in the room at 293 K. The maximum difference between the manual and the simulated results is 0.47. The heat transfer model employed in COMSOL is considered validated and deemed suitable for application in the subsequent phases of this study.

Figure 10 Comparison between the theoretical and published results for the dimensionless temperature distribution with respect to the dimensionless radius (see online version for colours)

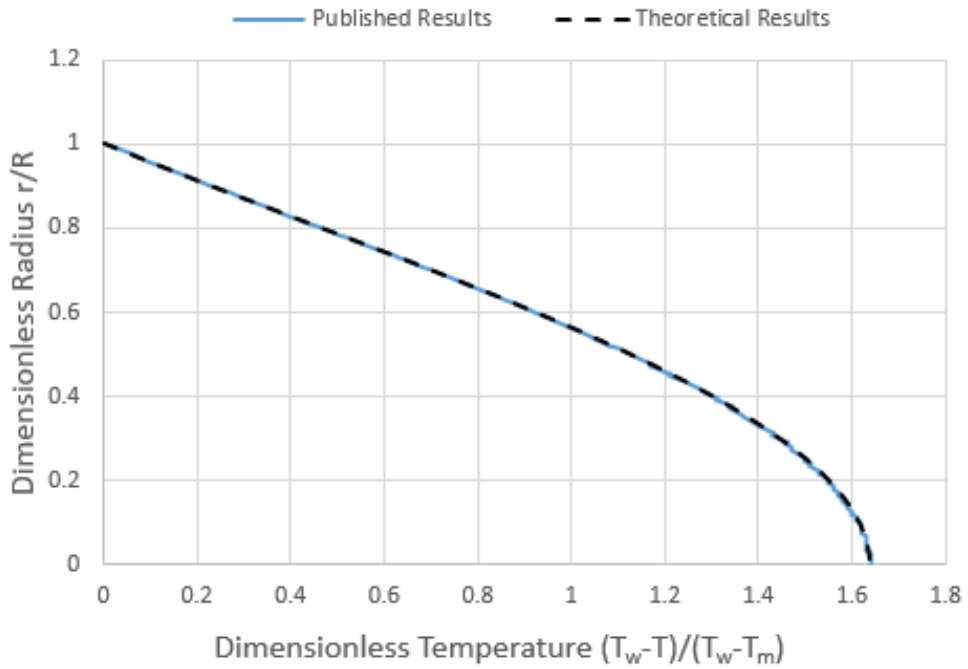


Figure 11 Trocar positional temperature distribution (see online version for colours)

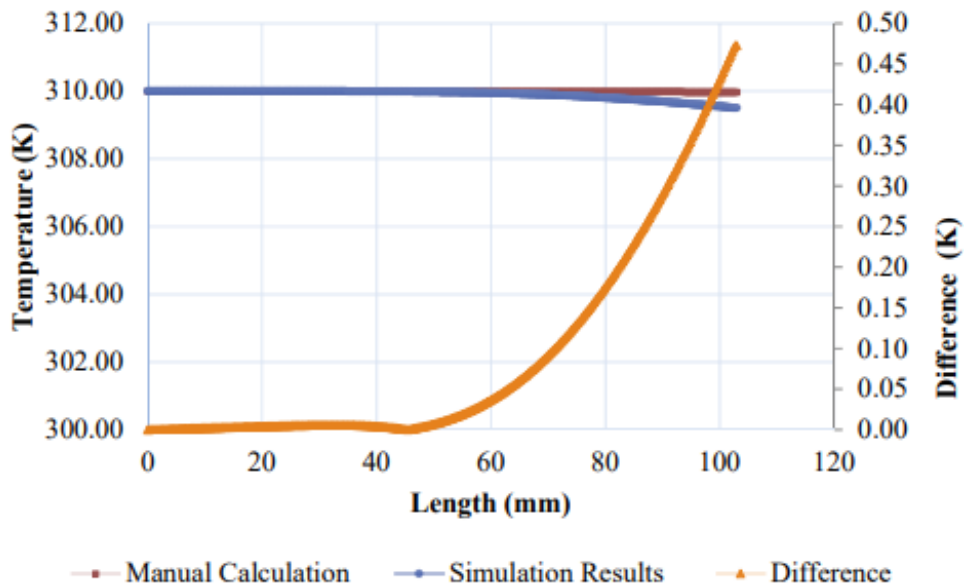


Figure 12 Thermal conductivity change (W/mK) of polycarbonate with increasing temperature (K) (see online version for colours)

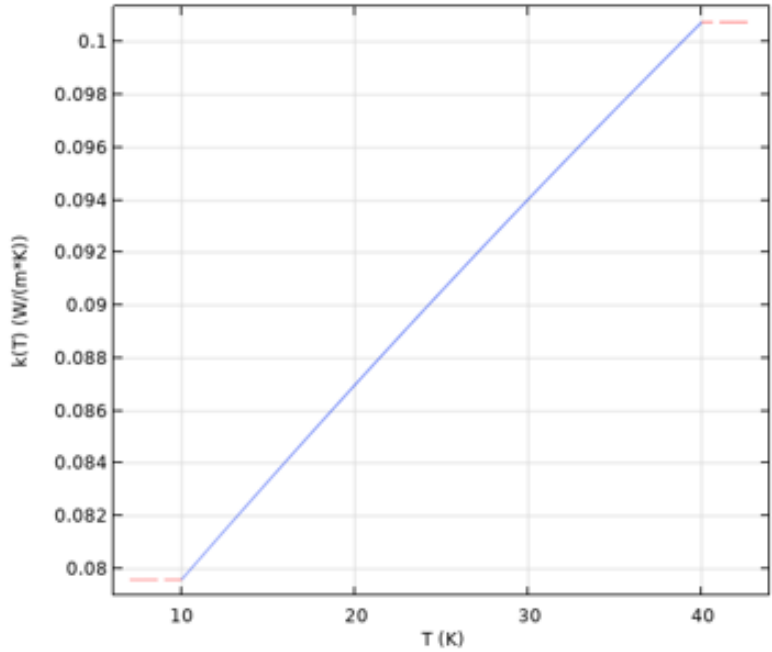
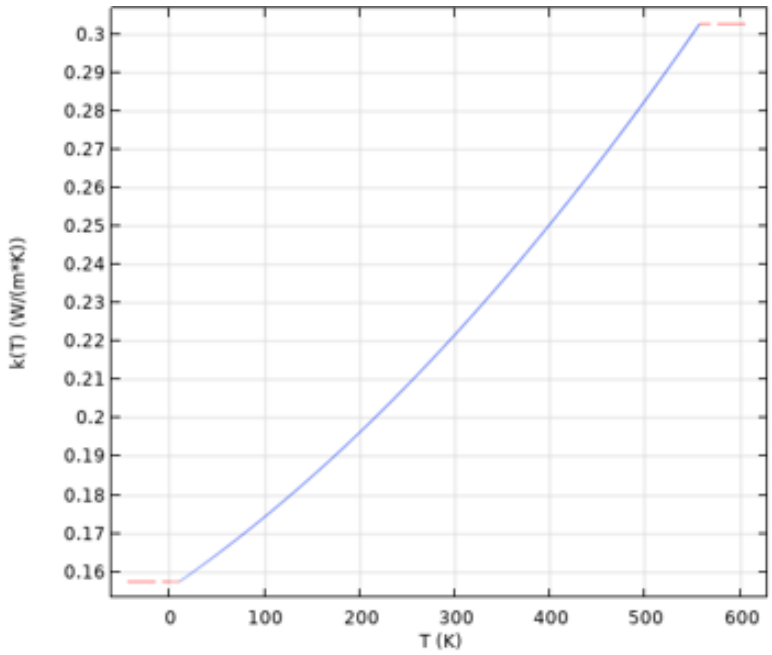


Figure 13 Thermal conductivity change (W/mK) of polyetherimide with increasing temperature (K) (see online version for colours)



3.2.1 Comparison between different materials

The commercial trocar is constructed from biocompatible materials like polycarbonate, polysulfone, acrylic, and polyetherimide, the latter being the newly introduced material. All these materials demonstrate similar thermal conductivity. The analysis of thermal conductivity entailed utilising the intrinsic material properties within COMSOL multiphysics.

Figure 14 Thermal changes along the axial distance at the core in various materials
(see online version for colours)

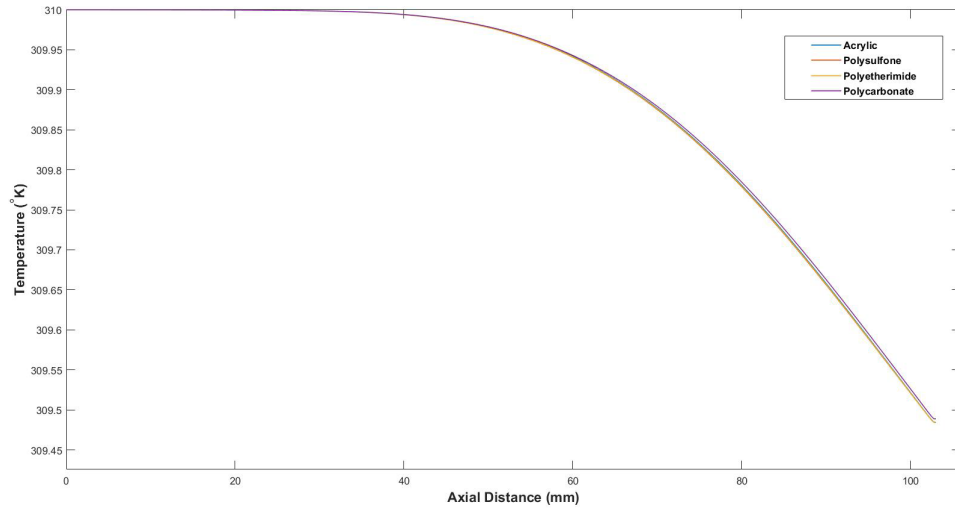
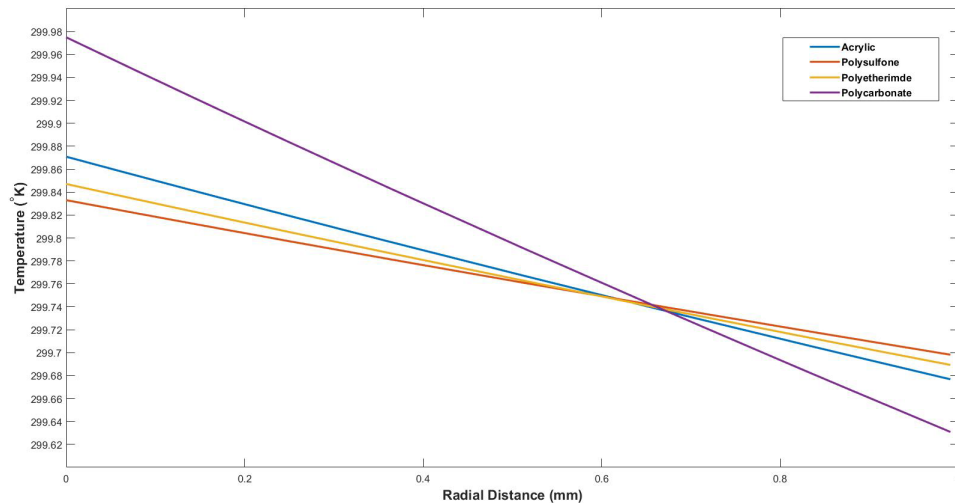


Figure 15 Thermal changes within the trocar wall thickness in different materials
(see online version for colours)



The thermal conductivity of acrylic (polymethyl methacrylate) and polysulfone showed constant values of 0.18 W/mK and 0.26 W/mK respectively over temperature elevation.

On the other hand, polycarbonate and polyetherimide revealed increasing thermal conductivity with temperature increase. These changes are shown in Figures 12 and 13.

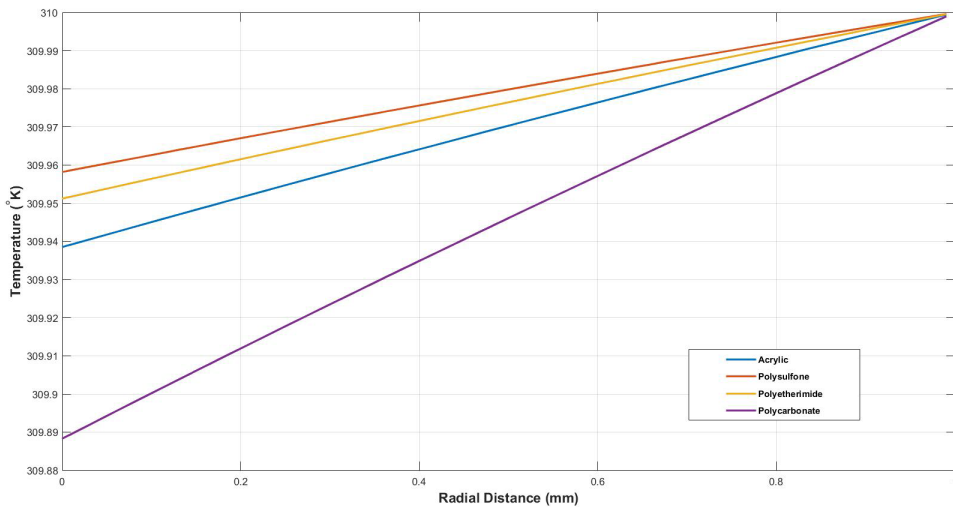
Figure 14 displays CO₂ temperature distribution obtained by COMSOL with the trocar made from four different materials. The temperature remains nearly constant in all materials at 310 K up to 40 mm from the inlet, then exponentially decreases, reaching 309.49 K at the end (103 mm).

Figure 15 illustrates the temperature variation across the thickness in different materials. The cut line used for plotting the graph was placed at $z = 95$ mm, where the flow is fully developed. The temperature gradient decreases from the interior surface in contact with heated carbon dioxide to the outer surface for all materials. Observing the curve, polycarbonate exhibits a higher temperature at the inner surface, followed by acrylic, polyetherimide, and polysulfone. However, after covering approximately 0.7 mm of the thickness, this ranking reverses, with the lower temperature at the outer surface becoming that of polycarbonate, and the higher temperature becoming that of polysulfone.

3.2.2 Heat transfer for actual conditions

The simulation results, under the specified model conditions and compared to the actual scenario, reveal a difference in the heat distribution within the material thickness. The related graph shown in Figure 16 is plotted for the material thickness at $z = 95$ mm, illustrating a temperature gradient from the inner surface to the outer surface for different materials. Initially, it indicates higher temperatures than the condition with no insertion into the body, with the order being polysulfone, polyetherimide, acrylic, and polycarbonate. All materials converge to a temperature of 310 K at the final position.

Figure 16 Thermal changes within the trocar wall thickness in different materials for real conditions (see online version for colours)



4 Conclusions

This paper reported an initial research of studying heat transfer through a trocar system. The obtained results shed light on certain aspects of the materials under investigation. The results shown for the trocar model surrounded totally with room conditions, indicate that all materials exhibit higher temperature at the inner portion of the material and lower temperature at the outer portion. This implies that all materials, including the newly introduced material, effectively preserve inner heat, maintaining it close to the temperature of carbon dioxide, while dissipating heat at the outer surface. The materials are ranked as follows: polycarbonate, acrylic, polyetherimide and polysulfone. This characteristic suggests that, with longer exposure, the material is subjected to less thermal stress.

Upon inspecting real conditions, results indicate that, at the initial position, the inner surface exhibits higher temperatures for all materials compared to the latter. In descending order, from higher to lower temperatures, the ranking is as follows: polysulfone, polyetherimide, acrylic, and polycarbonate. The temperatures follow a gradient pattern, ultimately reaching 310 K. According to the obtained results, the material experiences increased thermal stress when inserted into the body.

The achieved results represent a potent tool positioned for further enhancement. This adaptable and validated model holds the potential for extensive application with various materials and diverse boundary conditions. Its versatility allows for the exploration of superior materials under different scenarios. Beyond its original purpose of heat transfer observation, the model could evolve to depict stress-strain curves.

Contribution details

All authors have contributed equally to this work.

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