Heat Transfer in Laparoscopic Trocar System: Analytical and Numerical Study

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Abstract: In laparoscopic surgeries, CO_2 insufflation through a trocar system is required to fill the abdominal or pelvic cavity and provide a working space for the surgeon. The problem arises from the heat loss from the CO_2 gas to the surroundings of the trocar since it results in a temperature difference between the entering CO_2 and the temperature of the patient's body, which results in fog formation on the camera lens, blocking the surgeon's vision. This heat loss occurs by convection between the flowing fluid inside and outside the trocar and by conduction through the trocar's cannula. The primary objective of this research is to investigate the heat loss of CO_2 through the trocar cannula for different materials. These materials should meet specific requirements in order to be used in such surgery. The requirements are biocompatibility, transparency, eco-friendliness, and solid state. The selected materials are PET, PVDF, PEI, PEEK, and PC. Heat transfer and finite element analysis case studies were investigated to observe internal fluid flow behavior for velocity profile and temperature distribution. Then, a model was created and simulated on ANSYS workbench using proper boundary conditions that match real-life conditions. Comparative studies were done using ANSYS for the velocity profile, mean temperature distribution, axial temperature distribution, and radial temperature distribution of CO_2. The simulated results showed that PVDF was the best material to be used in the composition of the trocar's cannula since it resisted the most heat transfer, followed by PC, PET, PEEK, and PEI, respectively.

1 INTRODUCTION

Laparoscopic surgery, known as keyhole surgery, is an exploratory surgery that allows the surgeon to explore and examine the abdominal and/or pelvic cavities through a simple mechanism performed by creating a small incision near the belly button or pelvic bone and inserting a narrow surgical tube called a trocar through this incision. A trocar is a specialized medical equipment that acts as a port for different uses, such as the insertion of surgical instruments and carbon dioxide (CO_2) insufflation. The carbon dioxide insufflation is done by inserting a gas tube into the trocar to fill the patient's abdominal or pelvic cavity with CO_2 gas in order to separate the abdominal wall from other organs for clearance and more visibility of the examined area on the video monitor (Cleveland, 2024).

During CO_2 insufflation operation, heat loss occurs from the CO_2 passing through the trocar into the patient's body by conduction and convection due to the temperature difference between the CO_2 flowing in the trocar, which has the same temperature as the abdominal cavity initially, and the operation room's low temperature. This heat loss creates a difference in temperature between the CO_2 entering the body and the body's temperature, which leads to condensation on the camera lens that separates them. The condensation will result in water vapor formation on the camera lens, which will fog the surgeon's view during the surgery.

Here, the trocar is modeled as a pipe with an internal fluid flow. This assumption was made for comparison with a numerical and experimental heat transfer study conducted on an internal laminar fluid flow to observe the velocity magnitude with respect

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to the tube diameter (Al-Obaidi, 2021). It was observed that the velocity profile resulted in a parabolic shape. A study was done on a pipe with internal turbulent water flow exposed to a constant wall temperature of 500 K, 750 K, and 1000 K (Al-Zaharnah, 2004). It was observed that the dimensionless temperature increases when the studied point is farther away from the center, closer to the inner radius, and toward the end of the pipe. This increase in the dimensionless temperature means that the fluid's temperature is increasing. Another study on ANSYS and MATLAB shed light on the heat loss in a pipeline with multiple insulation layers with an internal turbulent fluid flow (Patil, 2016). The pipe layers consisted of glass wool, aluminium foil, and steel with different thicknesses. It was observed that the initial temperature of the steam flowing inside the pipe, at 0 m in length, was 503 K. Then, it decreased gradually throughout the pipe's length to reach a temperature of 423 K. A study on a vertical hollow cylinder having specific dimensions was done on ANSYS (Chandrakar, 2021). The cylinder having an internal fluid flow and exposed to high and low temperatures was studied. At lower temperatures, 350 K and 400 K, the convection and radiation heat transfer rates increased similarly. At higher temperatures, 450 K to 550 K, the increase in heat transfer rate by radiation was higher than that by convection. A heat transfer study using the orthogonal collocation method was done on a circular tube with laminar and fully developed internal fluid flow, exposed to a constant wall temperature (Belhocine, 2016). The dimensionless temperature decreases exponentially when the fluid moves towards the end of the tube, which means that the temperature of the fluid is getting higher and is thus getting closer to the high wall temperature.

The material of the trocar's cannula must be precisely selected to meet the proper material requirements which are: biocompatibility, transparency, eco-friendliness, and solid state. The material should also be able to have minimal heat transfer; it should act as an insulation material. Multiple materials will be selected while adhering to these requirements in order to reduce heat loss in the trocar's cannula during the CO_2 insufflation operation, which will reduce the condensation occurring on the camera lens. A simulation on ANSYS workbench will be conducted to compare the heat loss through the trocar using different materials in the cannula composition under real-life conditions. The trocar is modeled as a tube with an inner and outer diameter. The CO_2 fluid will flow through the inner diameter, and the tube will be exposed to ambient air flow with a low temperature at the outer diameter. The outcome of the numerical study will determine the temperature distribution that will be observed along the trocar.

An ANSYS simulation for the velocity profile will take place, and then it will be validated using theoretical equations and a previous published case study. After that, the mean, axial, and radial temperature distributions will be simulated in order to find the best trocar material to resist heat transfer.

2 METHODOLOGY

The trocar is modeled based on the characteristics of the commercial trocar system from XNY Medical, a manufacturer and distributor of minimal invasive surgery (MIS) medical devices, China. The trocar is considered to be a hollow tube with an internal CO_2 fluid flow and a surrounding ambient operating room temperature of 20 ºC causing natural convection, as shown in Figure 1.

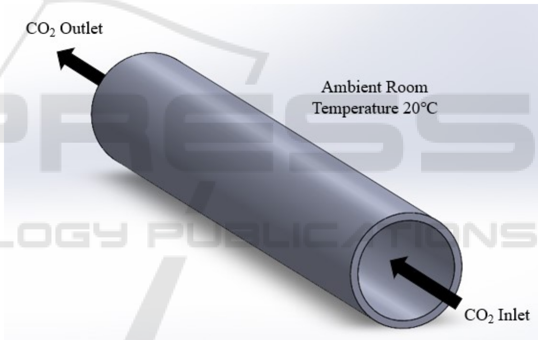

Figure 1: Trocar Model.

2.1 Material Selection

In the medical field, it is important to abide by the specific material requirements, which are, in this case, biocompatibility, transparency, eco-friendliness, and solid state. By definition, biocompatible materials are polymers, metals, and ceramics that don't produce an immune or toxic response within the human body. It is vital for the trocar to use a biocompatible material since it protects the patient from adverse reactions such as infection, toxicity, or an allergic response when it's inserted into the body. Another material requirement to take into consideration is the trocar's optical transparency, since it helps the surgeon visualize the tissue layers before the trocar's insertion in order to prevent organ injury (Tanaka, 2019). Finally, it's important for trocars to have a solid state and to be composed of eco-friendly material.

The common trocar's materials that meet these requirements are PolyEthylene Terephthalate (PET), PolyVinyliDene Fluoride (PVDF), PolyCarbonate (PC), Poly-EtherImide (PEI), and Polyether Ether Ketone (PEEK).

2.2 Numerical Model

The trocar is modeled as a hollow tube, as shown in Figure 2, that has the geometry shown in Table 1. This tube has a solid state and its properties were set according to the materials tested. The CO_2 fluid passing through the trocar was modeled as a cylinder. This cylinder has a fluid state to represent the CO_2 and the suitable properties of CO_2 were inserted. When it comes to the ambient air surrounding the trocar, a rectangular box was modeled as fluid to represent the air flowing in the room, causing natural convection.

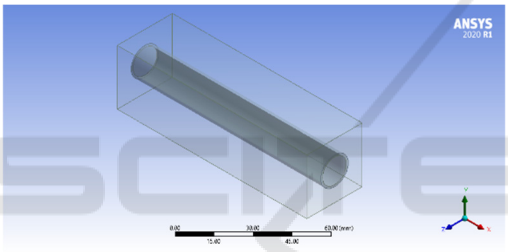

Figure 2: Trocar Model in ANSYS.

Table 1: Dimensions of the model components.

Parameter	Value
Tube Length	103 mm
Inlet Diameter	13 mm
Outlet Diameter	15 mm
Tube Thickness	1 mm
Box Length	30 mm
Box Width	103 mm
Box Height	30 mm

In the trocar model simulation, the boundary conditions are set to match the operating room conditions, where the CO_2 insufflation operation takes place. The CO_2 entering the trocar has an initial temperature and a volumetric flow rate which are shown in Table 2. On the other hand, the ambient air surrounding the trocar has a temperature and a velocity magnitude, which create a constant heat flux on the surface of the trocar. A box was created to represent the ambient air surrounding the trocar. The constant heat transfer coefficient of the CO_2 is calculated and set on the surface of the inner diameter of the trocar. In addition, the heat transfer coefficient of air is assumed, according to the range of typical values of free convection gases, and set on the surface of the outer diameter of the tube (Incropera, 1996).

Table 2: Simulation conditions.

Parameter	Value
Tube Length	103 mm
Inlet Diameter	13 mm
Outlet Diameter	15 mm
Tube Thickness	1 mm
Box Length	30 mm
Box Width	103 mm
Box Height	30 mm

2.3 Velocity Profile

The internal volumetric flow rate of CO_2 in this study during the CO_2 insufflation operation is assumed to be in the range of 0.1 to 3 L/min. First, the mesh sensitivity will be studied. Second, the velocity profile will be simulated on ANSYS, and then the theoretical equations will be gathered. After that, a comparative study will take place between the results of the simulation, theoretical, and a previous case study in order to validate the ANSYS model.

2.3.1 Model Mesh Sensitivity

Meshing has an important role in modeling and simulation since it is a method of breaking down the model into elements by generating grids. Meshing is used to discretize and analyze the simulation. The mesh types that are used in the ANSYS simulation are the linear, quadratic, program-controlled, tetrahedral, and hexa core types. A comparative study of the velocity profile between the theoretical and the simulation at 0.5 L/min internal flow using different types of mesh at 1 mm mesh size will indicate the most accurate mesh type. Figure 3 represents the variation of speed with respect to the radial position.

The velocity profile for the internal CO_2 fluid flow is shown to have a parabolic shape. It was observed from the results above that the quadratic and the program-controlled mesh types had the closest peak speeds and parabolic shapes to the theoretical results, which makes them the most accurate types of mesh.

The mesh element size indicates the accuracy of the results and the number of meshes required for the model to be divided into, which means that a smaller element size will give more accurate results (Dutt, 2015). A comparative study of the velocity profile between the theoretical and the simulation at 0.5 L/min internal flow using quadratic mesh having

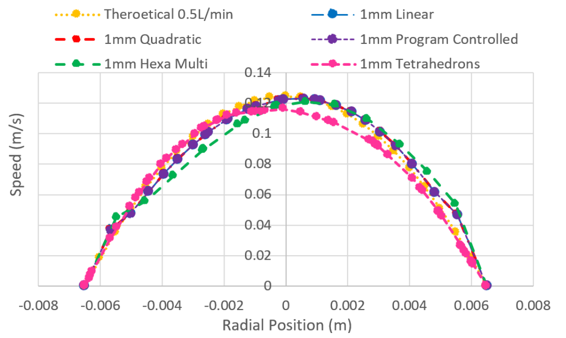

Figure 3: Variation of the speed for different mesh types with respect to the radial position.

different element sizes of 0.5, 0.75, and 1 mm, will indicate the most accurate element size. Figure 4 represents the variation of speed with respect to the radial position.

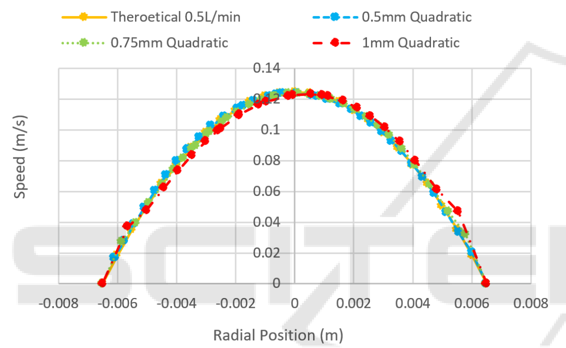

Figure 4: Variation of the speed for different mesh element sizes with respect to the radial position.

According to the results above, the 0.5 mm element size was the most accurate since it was the closest to the theoretical peak speed and the nearest to the theoretical parabolic shape. Therefore, the 0.5 mm quadratic mesh will be used for further simulations since it has the highest mesh sensitivity.

2.3.2 Analytical Model

To indicate the type of internal flow, Reynolds number will be studied at different volumetric flow rates. The Reynolds number is expressed as:

$$Re = \frac{\rho \times u \times d_i}{\mu} \quad (1)$$

Where Re is Reynolds number (unitless), ρ is the fluid's density (kg/m^3), u is the fluid's speed with respect to the cylinder (m/s), d_i is the cylinder's inner diameter (m), and μ is the fluid's dynamic viscosity (kg/m.s) (Incropera, 1996).

Using Equation 1, Reynolds number has a range of 18.879 to 566.38 over the volumetric flow rate range, which means that the internal CO_2 fluid flow is laminar since Reynolds number is less than 2300 (Incropera, 1996).

The equation of the dimensionless velocity profile of a laminar flow in a cylinder is represented by:

$$\frac{u(r)}{u_m} = 2 \times \left[1 - \left(\frac{r}{r_i}\right)^2\right] \quad (2)$$

Where u_m is the mean speed of the fluid (m/s), r is the radius of the studied location (m), and r_i is the inner radius of the cylinder (m).

To validate the ANSYS model, a comparative study will take place between the simulated results, theoretical results, and a previous published case study for the velocity profile. A previous published paper studied internal water flow in a pipe having a 0.5 m inner radius, a 1 m pipe length, and a maximum speed of 0.7 m/s (Najmi, 2017). After plotting the dimensionless speed with respect to the dimensionless radius for each one, as shown in Figure 5, it was observed that they had similar curves, which validates the ANSYS model.

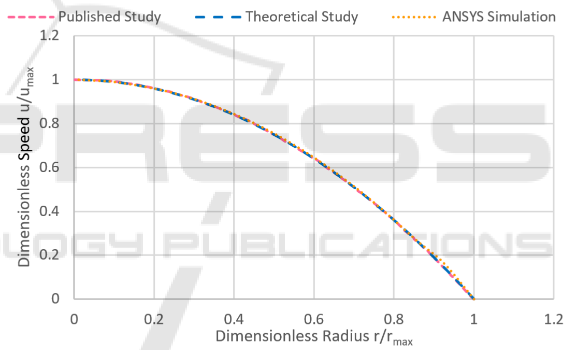

Figure 5: Dimensionless speed with respect to dimensionless radius for different studies.

2.4 Heat Transfer

During CO_2 insufflation operation, heat transfer in the trocar takes place by convection (both externally and internally) and conduction. The external convention occurs between the trocar surface and the air inside the room, while the internal convection occurs between the moving CO_2 gas inside the trocar and its walls. The conduction occurs through the thickness of the trocar's cannula. To compare the materials used in the trocar's composition, a thermal comparative study will be done on ANSYS using different trocar materials. The boundary conditions were properly set in ANSYS Fluent, as previously stated. The material of the tube was assigned separately to be PET, PVDF, PC, PEI, and PEEK, along with their properties. The mean, axial, and radial CO_2 temperature distributions were simulated on ANSYS as shown in Figure 6.

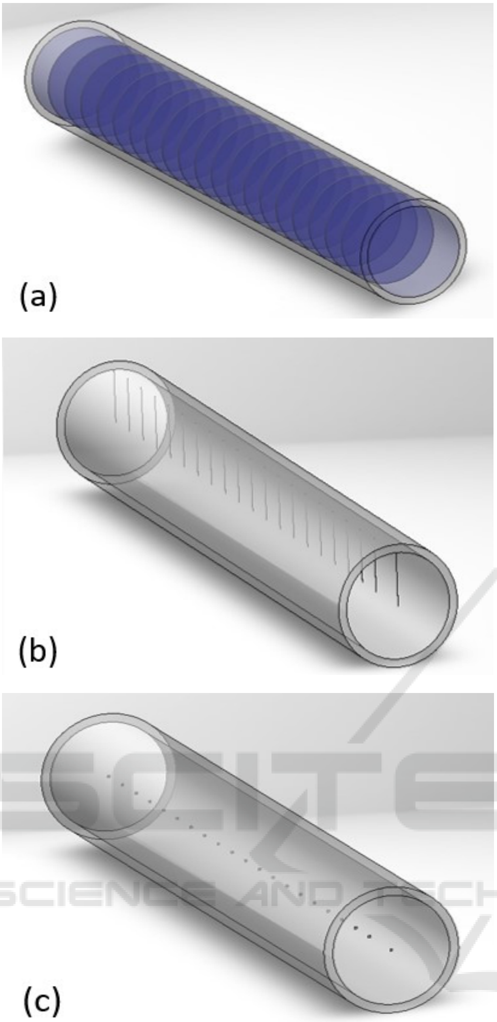

Figure 6: (a) Mean Temperature Distribution Simulation, (b) Axial Temperature Distribution Simulation, (c) Radial Temperature Distribution Simulation.

3 RESULTS

3.1 Mean Temperature Distribution

After simulating the ANSYS model, the results of the mean temperature were obtained along the axial position with an increment of 5 mm, as shown in Figure 7.

To analyze Figure 7, all the mean temperature curves using different materials started at 37 °C at the inlet of the tube. Then, they reached different values at the end of the tube, at 0.103 m, using different materials. It was observed from the results that the material that most resisted heat transfer was PVDF,

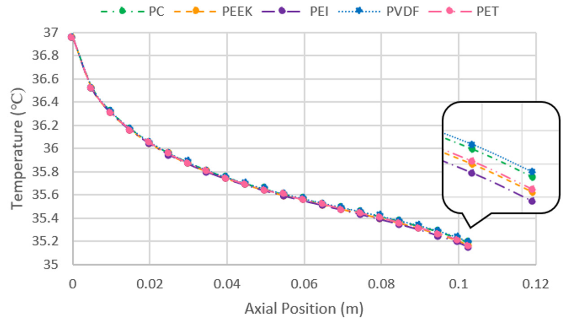

Figure 7: The mean temperature distribution of CO_2 at the axial position using different materials.

which has the lowest thermal conductivity of 0.185 W/m.K. PVDF showed the highest CO_2 mean temperature of 35.188 °C, which is the closest to the CO_2 initial inlet temperature, 37 °C. PC showed a lower mean temperature of CO_2 than PVDF followed by PET and PEEK, respectively. Finally, the least material that resisted heat transfer was PEI, which has the highest thermal conductivity of 0.328 W/m.K. PEI had the lowest mean temperature of 35.143 °C, which is the farthest away from the CO_2 initial inlet temperature.

3.2 Axial Temperature Distribution

After simulating the ANSYS model, the results of the axial temperature were obtained along the axial position, as shown in Figure 8. The temperature of the internal CO_2 fluid started at 37 °C and then started to decrease along the trocar's length to reach different values at the end of the trocar using different trocar materials. It was observed that the trocar material that resisted CO_2 heat loss the most along the length of the trocar was PVDF. This is because it has the lowest thermal conductivity of 0.185 W/m.K and the CO_2 temperature decreased the least from 37 °C at the beginning of the trocar to 36.76132 °C at the end of the trocar. PC resulted in a lower axial temperature of

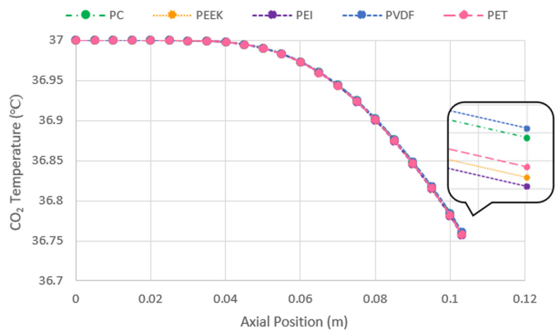

Figure 8: Distribution of CO_2 along the axial position using different materials.

CO_2 followed by PET and PEEK, respectively. Finally, the least material that resisted heat transfer was PEI, which has the highest thermal conductivity of 0.328 W/m.K and resulted in the lowest axial temperature, which is the farthest from the CO_2 initial inlet temperature.

3.3 Radial Temperature Distribution

After simulating the ANSYS model, the results of the radial temperature were obtained along the radial position, as shown in Figure 9.

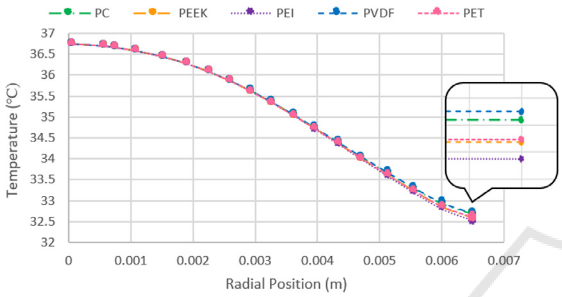

Figure 9: Temperature distribution of CO_2 with respect to the radial position using different trocar materials.

Figure 9 shows the temperature distribution of CO_2 along the radial position. For all materials, the curves start at a specific peak value at the center of the trocar and then decrease as they get closer to the inner wall of the trocar. It was observed that the CO_2 temperature at the inner wall of the trocar was the highest, with a value of 32.699 °C, when the trocar material was PVDF. The temperature difference was the lowest, 3.569 °C, which means that PVDF exhibited the highest resistance to heat transfer. Following that is PC, which showed a lower CO_2 temperature at the inner wall of the trocar and a greater temperature difference; next is PET, followed by PEEK. The material that resisted heat transfer the least was PEI, which had the lowest CO_2 temperature at the inner wall, with a value of 32.524 °C, and the highest temperature difference of 3.734 °C.

4 CONCLUSIONS

In laparoscopic surgeries, during CO_2 insufflation, the CO_2 entering a patient's body at 37 °C through the trocar loses heat due to its surroundings. This temperature difference causes fog to form on the camera lens inside the body. In order to mitigate this heat transfer, multiple materials that can be used in the composition of the trocar were compared to determine which material results in the least temperature difference between the inlet and outlet of the trocar, thereby reducing condensation. The selected materials are PET, PVDF, PEI, PEEK, and PC.

The trocar was modeled using ANSYS Fluent Fluid Flow, where proper boundary conditions and geometry were applied to match the trocar and the operating room conditions. The ANSYS simulation was validated by a comparative study with the theoretical equation and a previous case study.

The mean, axial, and radial temperature distributions using each of the five materials in the composition of the trocar were plotted using ANSYS.

Results showed that PVDF, having the lowest thermal conductivity, had the highest resistance to heat transfer with a CO_2 mean temperature of 35.18817 °C and an axial temperature of 36.76132 °C at the end of the trocar's length. It was followed by PC, PET, PEEK, and PEI. Moreover, the CO_2 radial temperature distribution indicated that PVDF also had the highest resistance to heat loss radially with a CO_2 temperature difference of 3.569 °C from the center to the trocar inner surface at the end of the trocar, followed by PC, PET, PEEK, and PEI.

In summary, the best material that can be used in the composition of the trocar is PVDF since it has the greatest CO_2 heat loss resistance throughout the length of the trocar, which will result in the least fog formation on the camera lens.

As a future plan, an experimental study will be performed using different trocar materials in order to study the actual CO_2 temperature distribution along the trocar. Validating the numerical and computational methods using an experimental study will lead to refining the model and confirming the optimal material to be used in the trocar composition, which will result in minimal CO_2 heat loss to prevent fog formation.

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