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Technical note

Simulation of carbon dioxide insufflation via a diffuser in an open surgical wound model

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ABSTRACT

Flow within a model surgical opening during insufflation with heated carbon dioxide was studied using computational fluid dynamics. A volume of fluid method was used to simulate the mixture of ambient air and carbon dioxide gas. The negative buoyancy of the carbon dioxide caused it to fill the wound and form a protective layer on the internal surfaces for a range of flow rates, temperatures, and angles of patient inclination. It was observed that the flow remained attached to the surface of the model due to the action of the Coanda effect. A flow rate of 10 L/min was sufficient to maintain a warm carbon dioxide barrier for a moderately sized surgical incision for all likely angles of inclination.

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1. Introduction

Intraoperative insufflation of the open surgical wound with carbon dioxide (CO₂) has been used for several decades to de-air the open chest wound in open heart surgical procedures including cardiac valve surgery. More recently, it has been proposed as a convenient intraoperative method to reduce the incidence of post-operative surgical site infection (SSI), a common severe and costly complication after surgery. CO₂ is beneficial in maintaining the temperature in the wound and there is evidence that temperature plays a role in tissue perfusion and oxygenation [1]. Local warming also influences the body core temperature. In open surgery, a substantial amount of the total heat lost during surgery is through the open surgical wound via radiation and evaporation, which reduces the core temperature [2,3]. Insufflated CO₂ is a greenhouse gas that reflects radiant heat from the wound and thus warms exposed wound surfaces [4]. If heated and fully humidified, the insufflated CO₂ warms the wound further and also prevents evaporation from the wound surfaces, which otherwise will cause cooling of the wound when it is exposed to relatively dry ambient air [5]. Other proposed mechanisms of action include decreased airborne contamination [6,7], reduced bacterial growth [8], and improved tissue oxygenation [9]. The method is dependent on a gas insufflation device that creates a local atmosphere of CO₂ in the open wound, covering the inner surfaces [10].

There is a lack of understanding of the flow dynamics of insufflated CO₂ in the wound at the clinically used flow rate of 10 L/min, since the CO₂ gas is not visible in gaseous form and problematic to visualise. Present understanding is based on sampling of gas from different positions in the open wound during insufflation and tissue perfusion data [11]. However, computational fluid dynamics (CFD) is a potential method for illustrating the insufflation gas dynamics in order to understand and improve the technique.

In this work CFD was used to model the delivery of CO₂ into an open wound cavity through an insufflation tube that terminates in a gas diffuser (VITA-diffuser[®], Cardia Innovation AB, Stockholm, Sweden). The aim of the study was to investigate the flow of CO₂ in an inclined elliptical cavity, which is representative of an open abdominal surgical wound, whereby the local volume fraction of CO₂ as a function of time is the primary variable of interest. Specifically, large eddy simulation has been used to visualise the mean distribution and flow evolution of CO₂ for a range of possible wound inclinations.

2. Methodology

2.1. Flow domain

The surgical incision model was an ellipse 45 mm deep with major axis 185 mm and minor axis 115 mm as shown in Fig. 1. The major axis of the ellipse was aligned with the x-axis of the domain, the minor axis in y, and z was the vertical direction. The inner edges of the ellipse were smoothed with a radius of 10 mm. A fluid domain

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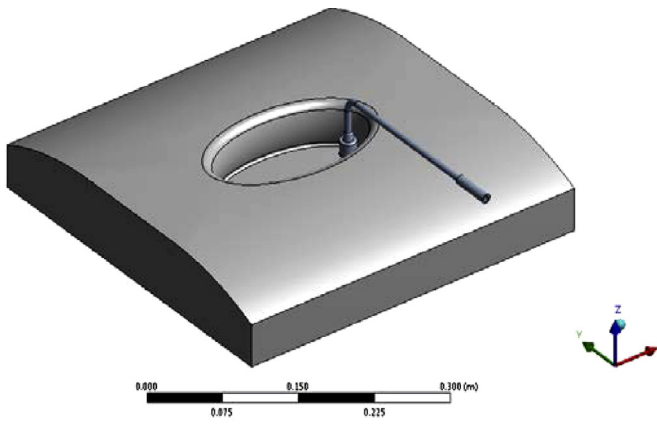


Fig. 1. Geometric arrangement, showing wound model and diffuser position.

also of interest. Therefore, a range of model inclination angles were simulated, from 0° to 22.5° rotation around either the x or y axes in increments of 2.5° .

2.2. Mesh generation

A suitable mesh for the flow solver was created by first generating a triangular surface mesh. This used an advanced size function that sizes surface elements based on local geometric curvature. The minimum edge length for the triangles was 1.21 mm. Programme controlled inflation layers were generated to increase the number of nodes near solid surfaces using a smooth transition ratio of 0.77 with a maximum of 5 layers and a growth rate of 1.2. The surface mesh was used to generate a complete unstructured tetrahedral fluid domain mesh and a mesh resolution study was conducted to confirm that the solution is independent of the mesh and sufficient to capture the dynamics of the fluid motion. The mesh used for all following flow simulations had approximately 180,000 nodes and 590,000 elements.

2.3. Initial and boundary conditions

The fluid domain was solved as a continuous fluid with a reference pressure of 1 atm. (101.3 kPa) using ANSYS CFXTM 11.0. Air properties were referenced from an included material library and

was generated by creating an enclosure around the solid geometry with a total domain size of 50 cm \times 42 cm \times 19 cm.

The diffuser tip was situated at the narrow end of the wound and aligned with the major axis of the ellipse at a depth of less than 30 mm. A small parametric study showed that the gross flow field was insensitive to diffuser depth and position when the model is level. However, possible inclination of the patient or wound is

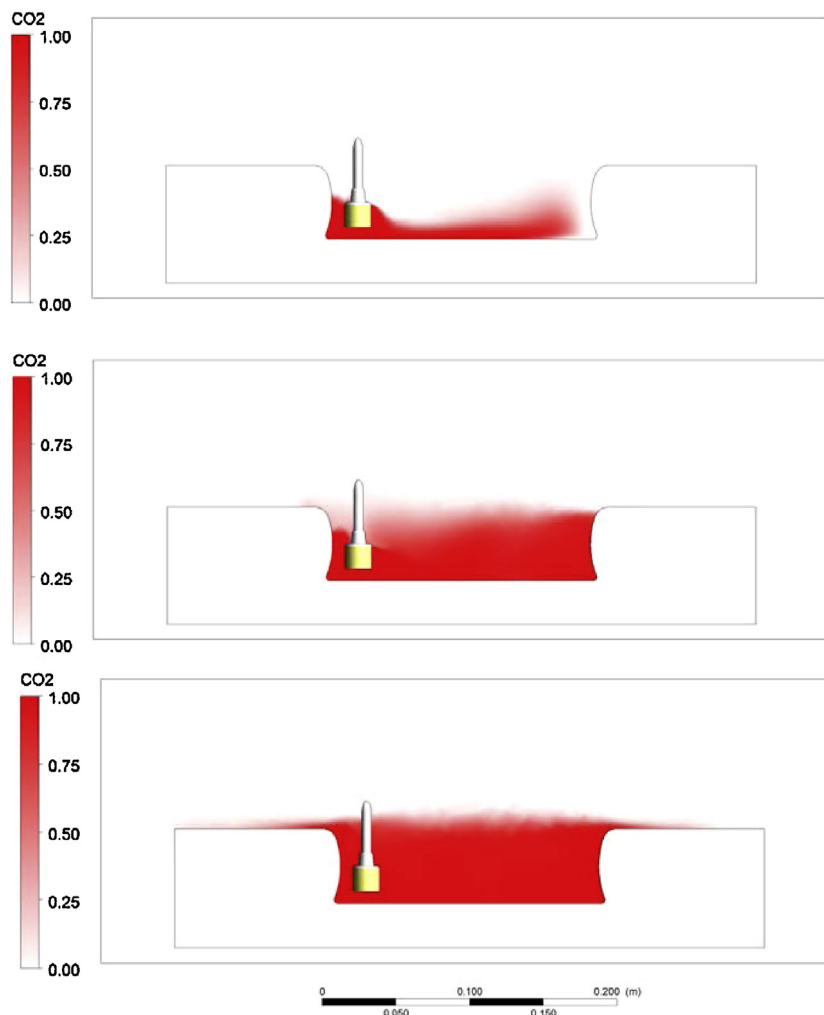


Fig. 2. CO₂ volume fraction results for 10 L/min flow at different instants (1 s, 3 s, 5 s).

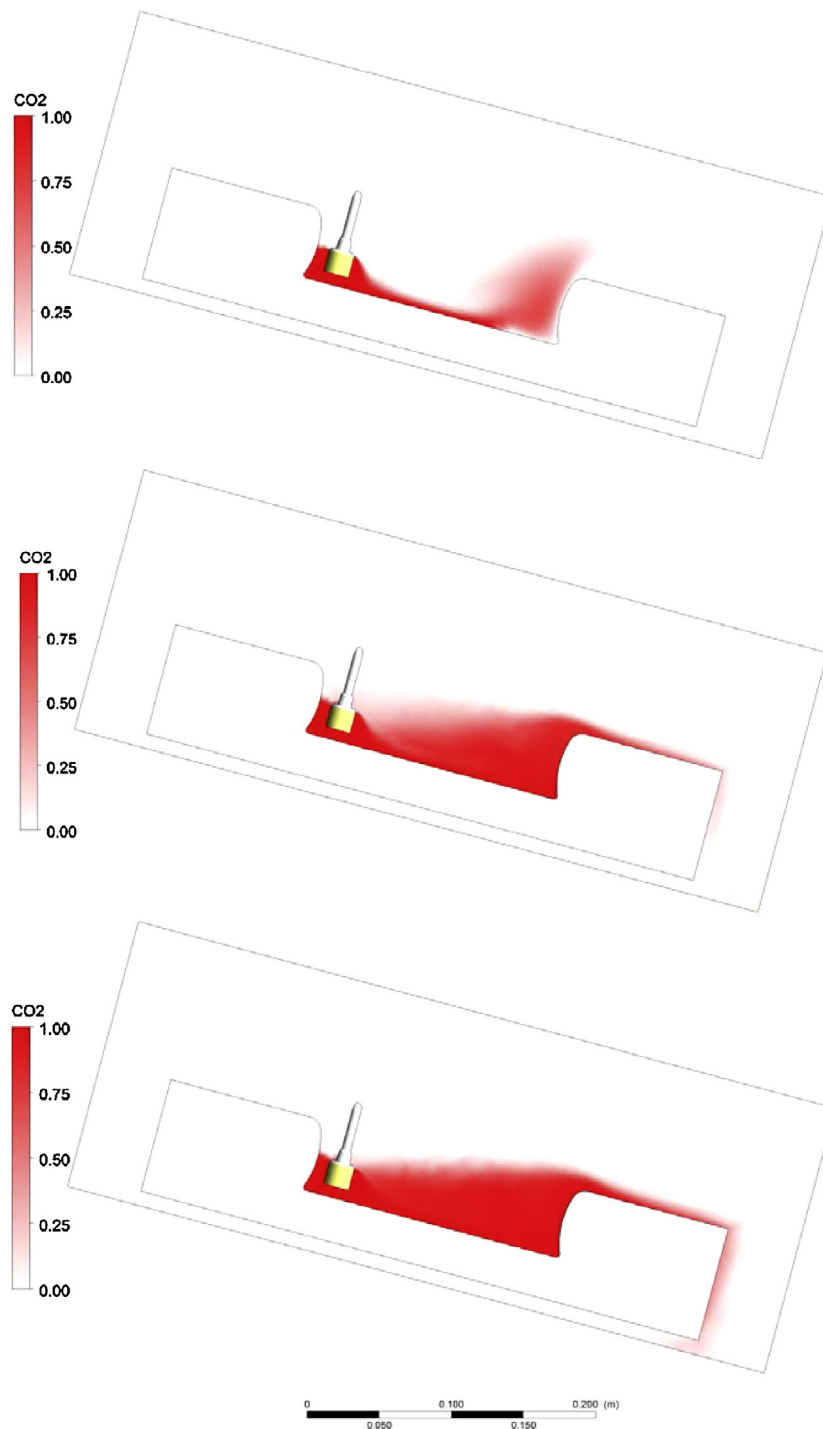


Fig. 3. CO₂ volume fraction results for 10 L/min flow tilted at 15° at different instants (1 s, 3 s, 5 s).

the initial ambient temperature was 24 °C. CO₂ was modelled as an ideal gas with an initial temperature of 37.5 °C. The fluid domain was modelled as a homogeneous phase using a volume of fluid method; this allowed a proportion of both gases to exist in any mesh volume. A buoyancy model was used with a reference density of 1.185 kg/m³. Gravitational acceleration was -9.81 m/s^2 in the z direction. Local density differences were then used to solve for the buoyancy forces. At the solid boundaries, a no-slip condition was imposed. All other domain boundaries had zero relative pressure applied and ‘opening’-type boundary conditions. This allowed gas of either type to pass into and out of the domain as required.

The diffuser had a mass flow rate of CO₂ specified as an ‘inlet’ type boundary condition (flow was not permitted to flow back through the diffuser).

2.4. Solution parameters

It was necessary to solve a time-evolving (transient) flow problem, initialised using an air-filled domain. A physical steady-state solution was not found using Reynolds-Averaged Navier–Stokes methods (RANS) since an asymptotic solution for these conditions consists of the entire domain filled with CO₂ at the reference

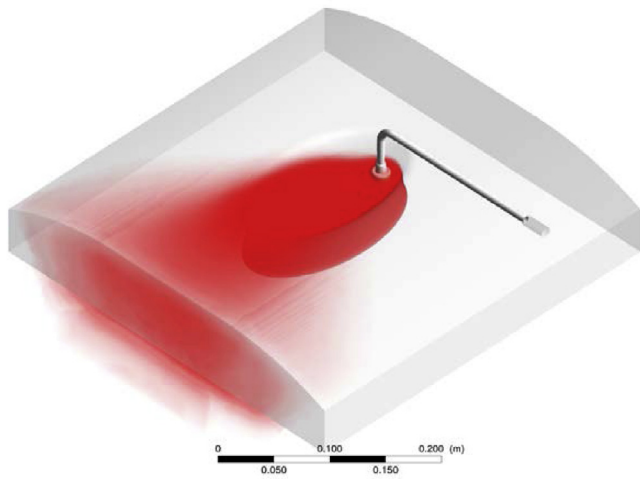


Fig. 4. CO₂ volume fraction results for inclined wound geometry at 10 L/min, tilted 15° after 9 s of simulated flow. Intensity indicates the relative fraction of CO₂ in the local volume (g).

pressure. A transient solution also permitted the time-evolving distribution of CO₂ in the wound to be studied. Model investigations that have compared the degree of air displacement achieved by the gas-diffuser show that when accounting for suction, a flow rate of 10 L/min is required for most efficient insufflation into a surgical wound [12]. To verify this result a range of flow rates was tested, from 3 to 10 L/min.

In initial testing using large eddy simulation [13], turbulent activity was found to be insignificant in the mixing and gross flow behaviour of the gases, so that during the final simulations a laminar flow closure model was used with a High Resolution Advection scheme for momentum transport. Time-stepping was second-order backward Euler. At each timestep, 3–5 coefficient loops were used with an RMS residual target of 1×10^{-3} . The timestep duration was 0.05 s, with 200 timesteps; this was found to be sufficient to permit quasi-steady flow fields to develop, where the amount of CO₂ leaving the domain equals that supplied through the diffuser at the end of the simulation. Solutions took approximately 4 h each using 4-cores of an Intel Core u5-2549M CPU @ 2.6 GHz with 8 GB of RAM to calculate 200 timesteps.

3. Results

3.1. Flow development results

In initial numerical experiments, a horizontal wound orientation was used to investigate the effect of simulation duration on the flow patterns. The volume fraction of CO₂ is displayed in the x - z plane for a series of instants in Fig. 2. These planes are sampled along the major axis of the ellipse.

3.2. Inclined geometry results

Fig. 3 shows an example for the flow development when the geometry is inclined by 15° about the y -axis.

At the instant shown in Fig. 4 (9 s), all inclined simulations reach a quasi-steady state, where the interface between the air and CO₂ is approximately level and the inner surfaces of the wound are covered by high volume fractions of CO₂. The excess CO₂ flows over the low edge of the wound and remains attached to the surface of the patient model due to the action of the Coanda effect, which is the tendency for faster moving fluid to be attracted to an adjacent surface [14]. The near-wall flow creates a region of low pressure

that entrains fluid from above. This phenomenon permits the flow to follow relatively large changes in the surface curvature.

4. Discussion

In all cases simulated the CO₂ is denser than the surrounding atmosphere and filled the wound to approximately level, before flowing over the lowest edge of the model incision and leaving through the lower surface of the domain. At 10 L/min, the wound was filled with CO₂ after approximately 6 s in all inclinations simulated (see Figs. 2 and 3). However, at lower flow rates some small differences were observed. In particular, the cavity took a longer time to fill completely when level, as expected; buoyancy forces are relatively more important at low flow rates compared with inertial forces. These results suggest that the maximum tolerable angle for the wound is reduced as flow rate is reduced. There was a small local thickening of the layer of CO₂ around the diffuser that was visible when the flowrate was less than 5 L/min or when the geometry was inclined at angles larger than 12.5° (this thickening can be seen in the first plots of both Figs. 2 and 3). This is attributed to the local diffusion pattern around the diffuser. Further simulations showed that the flow was insensitive to variations in the temperature of the introduced gas and the ambient temperature over the range 24–50 °C.

For all the inclined flow simulations, there was some recirculation of the flow within the wound geometry, particularly below the lowest part of the wound edge (see the first and second plots in Fig. 3). This recirculation represented a small volume where CO₂ was resident for a longer period. More complex edge geometries are therefore likely to lead to more complex flow patterns within the wound. A limitation of this work is that the simulation models the surface of the model as a smooth rigid wall as shown in Fig. 1, whereas this is unlikely to be the case in a clinical application, particularly near the wound edges. Rough surfaces would add additional regions of local recirculation; these may decrease local heat and mass transfers.

5. Conclusions

The distribution of CO₂ in a surgical wound model has been studied using numerical flow simulation. The results indicate that the flow within the domain is laminar for CO₂ flow rates between 3 and 10 L/min. The supplied heated CO₂ was denser than the ambient air for a wide range of working temperatures and generally found a level meniscus such that excess CO₂ exited the wound at the lowest edge, and therefore it is recommended that the diffuser is placed at the highest end of the wound during this therapy. As CO₂ flowed over the surface of the patient model the flow remained attached to the surface due to the Coanda effect. There was recirculation of the flow within the wound, particularly below the lowest part of the wound edge; this region was larger for more inclined geometries. It is concluded that the maximum tolerable angle for a wound is increased as the flow rate of CO₂ is increased up to an inclination of 22.5° and 10 L/min.

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