Fluid Dynamics of Cytotoxic Safety Cabinets

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Received 15 July 2009; in final form 27 October 2009; published online 9 December 2009

This study investigated the specific fluid dynamics characteristics of cytotoxic safety cabinets (CSC), particularly those used in cancer drug reconstitution operations. Measurements taken on site were used to derive characteristic data for these cabinets. An in-depth laboratory investigation of airflows inside another CSC was also conducted. Anemometric values recorded on these two installations enabled the experimental validation of computational fluid dynamics methods applied to CSC. The digital flow simulations conducted provide a better understanding of the detailed flow structure inside a CSC and made it possible to study the influence of different operating parameters on the air velocity distribution inside the cabinet front opening: recycled air temperature, product protection airflow rate, suction openings spatial distribution, air compensation mode and draughts, operator arm penetration, and operator presence in front of the cabinet.

Keywords: anemometric measurements; computational fluid dynamics; cytotoxic safety cabinet; microbiological safety cabinet; velocity field; ventilation

INTRODUCTION

Short- and long-term toxicities of cytotoxic drugs manipulated by health facility staff during cancer chemotherapy operations are high (Ziegler et al., 2002; Burroughs et al., 2004). These products can enter the organism through cutaneous–mucous contact or aerosol inhalation. High-exposure risk would appear to be generated by conditions prevailing at product reconstitution stage (Mason et al., 2005); this involves diluting the drug (usually delivered in powder form) in an aqueous solution, then conditioning the prescribed volume in view of its administration. Conditions in which product reconstitution operations are performed must ensure both drug quality, especially asepsis, and staff protection. There is frequent recourse to simultaneous application of personal and collective protective equipment, the latter possibly comprising confinement enclosures (commonly called isolators) or Type II microbiological safety cabinets (MSC).

Type II MSC are ventilated enclosures under negative pressure featuring a front opening, through which the operator can manipulate the relevant products inside the cabinet (Fig. 1). The front opening allows an airflow $Q_1$ to enter the cabinet and counteract pollutant leakage towards the operator. A higher airflow $Q_3$ is extracted through suction openings built into the workbench, then conveyed to the top section of the MSC, where it is divided into two flows: one equivalent to airflow $Q_1$, which is extracted from the cabinet, and an airflow $Q_2$, which is re-introduced at the top of the cabinet working volume after very high-efficiency filtration. The specific characteristic of Type II MSC is created by sweeping of the cabinet-working volume by the unidirectional downward airstream flow $Q_2$, designed to ensure product protection from airborne contamination. These MSC are sometimes wrongly referred to as laminar flow cabinets.

Cytotoxic safety cabinets (CSC) are Type II MSC, which are dedicated to handling cytotoxic drugs. Balty et al. (2003) recommend that cabinets used for this application should possess the following specific equipment:
Flow control systems with alarms;
- A partially perforated workbench;
- An extracted air discharge system, indirectly connected to an exhaust network;
- Use of three very high-efficiency filters.

Concerning ventilation, informative appendices A and H of European Standard EN-12469 (CEN, 2000) provide the following performance criteria for Type II MSC:

- Front opening height: between 160 and 250 mm;
- Mean velocity of incoming airstream required to ensure operator protection: ≥0.4 m s⁻¹. This velocity is calculated from exhaust airflow measurement and the opening cross-sectional area;
- Mean velocity of downward airstream required to ensure product protection: between 0.25 and 0.50 m s⁻¹. This velocity is the mean of velocities measured at eight positions in a horizontal plane using an anemometer introduced into the cabinet;
- Deviation from the mean for each of the eight velocities measured in the downward airstream: <20% (uniformity criterion for product protection airstream).

The purpose of this paper is to characterize the specific fluid dynamics properties of CSCs, especially the air velocity distribution in the cabinet front opening. The confinement level provided by the cabinet depends in particular on the values of the horizontal component of velocity in the front opening; these values govern the incoming characteristic of the airflow generated to counteract possible pollutant leakage towards the operator. The paper analyses mutual interactions of the different airstreams inside the CSC, their interactions with the room ventilation system, and the influence of different CSC-operating parameters on the velocity fields. The study involved airflow measurements, anemometric measurements on site and in the laboratory, and digital flow simulations using computational fluid mechanics software.

The impact of operator and product protection relative airflows on overall MSC performance has been evaluated by Jones et al. (1990) using particulate microbiological tracers, but these authors did not characterize the concomitant air velocity field variations. Computational fluid dynamics methods have been applied by several authors, when studying fume cupboards (Johnson et al., 1995; Hu et al., 1998; Nicholson et al., 2000; Lan and Viswanathan, 2001; Chern and Cheng, 2007). These methods do not appear to have been previously applied to Type II MSC.

MATERIALS AND METHODS

Anemometric techniques

Air velocities were measured inside the CSC using a unidirectional and an omnidirectional anemometer. The latter instrument was a hot sphere model and featured a mark showing the reference orientation used during its calibration. A wind tunnel study was conducted to establish to what extent this instrument’s response depended on probe angle of rotation. This evaluation showed that the maximum error for all possible orientations was 4% for an air velocity of 0.3 m s⁻¹ and 10% for an air velocity of 1.4 m s⁻¹.

The unidirectional anemometer incorporated a hot wire positioned inside an oblong window at the end of a cylindrical rod. A wind tunnel study of probe directivity showed that the anemometer response effectively obeyed the theoretical cosine of airflow angle of incidence variation law for angles between −45° and +45°. When investigating in the laboratory, the air velocities in the vertical symmetry plane of a CSC, in which the longitudinal velocity component is zero, three measurements were taken at each point: one using the omnidirectional anemometer, which provided the velocity magnitude, and two using the unidirectional anemometer, successively orientated at 0° and 90° to the horizontal. In conjunction with the cosine variation law, the higher of these latter two measurements enabled the determination of the velocity vector inclination and thus the horizontal and vertical components of the air velocity.

Fig. 1. Diagrammatic representation of implemented airflows.
The anemometers were calibrated in a closed loop wind tunnel using a Doppler laser anemometry-based reference. A laboratory accredited in compliance with European Standard EN-17025 (CEN, 2005) by Comité Français d’Accréditation an International Laboratory Accreditation Cooperation member, performed this calibration operation.

Based on the calibration uncertainties, the anemometer reliability, and the hot sphere sensitivity to the relevant angle of incidence, the uncertainty in the velocities measured with the omnidirectional anemometer was 13%. Given the calibration uncertainties, the anemometer reliability, and the departure between the angular response and a cosine-type response, the uncertainty in the velocities measured with the unidirectional anemometer was 15%. Uncertainties related to probe positioning during site measurements were 1 mm in the flow direction and 5 mm in directions perpendicular to the flow. In the laboratory, probe-positioning uncertainties varied between 1 and 2 mm, depending on the measurement location.

**Measurements on site**

Airflow measurements were taken in a CSC in the main pharmacy of a hospital facility. The effective internal width of this CSC, fitted with three filters, was 1.796 m and it was located in an ~38 m³ room supplied by two ceiling diffusers. The height of the CSC front opening was 0.2 m and the workbench incorporated suction openings around its full periphery.

Air velocities were measured using a unidirectional anemometer in a horizontal plane 200 mm below the underside of the cabinet top filter and in the front opening vertical plane. Access to the exhaust duct proved impossible, so the airflow extracted by the cabinet was measured using streamlined balometer applied against the opening. This balometer was laboratory calibrated on an installation recreating flow conditions similar to those encountered on site.

**Laboratory measurements**

Laboratory measurements were taken on a CSC diagrammatically represented in Fig. 2. The effective working volume of this CSC was dimensioned as follows: width 1.190 m, depth 0.581 m, and height 0.660 m. The cabinet front opening (number 5 in Fig. 2) was 1.190 m wide and 0.200 m high. The front of the workbench incorporated two rows of 116 perforations 5 by 50 mm (number 3) and its rear incorporated one row of 116 perforations 5 by 25 mm (number 2). There were no perforations along its two short sides. Its front featured a 22-mm high bevelled edge. The number 1 in Fig. 2 represents the ceiling of the effective volume, comprising a filter through which the product $Q_2$ protective airflow is introduced. The number 4 in Fig. 2 represents the window delimiting the working volume in front. The airflow extracted by the CSC was discharged outside the testing cabin. When taking measurements, this airflow was compensated using ceiling-mounted fabric air to be delivered at low velocity and non-directionally;

- A 1.4 × 1.9 m rectangular supply plenum, without louvres, located in the centre of the ceiling, which ensured delivery of vertically directed air.

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socks and the testing cabinet operated without additional general ventilation. CSC nominal operating characteristics, determined by the manufacturer, were as follows:

- Airflow extracted through the cabinet front opening: \( Q_1 = 384 \, \text{m}^3 \, \text{h}^{-1} \), corresponding to a horizontal discharge velocity \( U_1 = 0.449 \, \text{m} \, \text{s}^{-1} \) and a Reynolds number of 10200;
- Product protection airflow recycled at top of cabinet.

Airflow velocities in unidirectional downward airstream were measured in a horizontal plane 290 mm below the cabinet top filter, using both an omnidirectional anemometer and the unidirectional probe. Mean velocities obtained using the two instruments differed by \(<2.8\%\). Longitudinal profiles of the velocity magnitude were recorded and an exploration of velocities in the cabinet vertical symmetry plane was also carried out.

The airflow by the cabinet was measured in the exhaust duct using a standardized orifice plate with pressure taps one diameter upstream of the orifice plate and half a diameter downstream connected to a very low pressure micro-manometer. Type K (Ni–NiCr) thermocouples were used to measure temperatures.

**Digital simulation methods**

Digital flow simulations were performed using the general purpose, fluid dynamics software programme FLUENT, version 6.3.26 (Fluent Inc., 2006). This programme uses an iterative process to solve the conservation equations (mass, momentum, turbulence, etc.) by applying the finite volume method for structured, unstructured or hybrid grids. Computation conditions used corresponded to 3-dimensional, single phase, incompressible, steady, turbulent and isothermal (except for one simulation, simulation E, described below) flows. Turbulence was simulated by the realizable k-epsilon model. The default values of the constants for this turbulence model were applied \((C_{2e} = 1.9; \sigma_k = 1; \sigma_e = 1.2)\). Steady-state resolution was performed without time steps.

The following boundary conditions were adopted in the simulations:

- Working volume ceiling (refer 1 in Fig. 2): imposed vertical, uniform velocity air inlet;
- Perforations in workbench (refer 2 and 3 in Fig. 2): imposed vertical, uniform velocity air outlets;
- Compensation air input openings in ceiling of chamber containing the CSC: imposed uniform velocity air inlets;
- Solid surfaces delimiting CSC and chamber: airtight walls with no-slip shear condition and application of wall functions (Fluent Inc., 2006).

The flow rate at each air inlet–outlet was uniformly distributed over the relevant surface. Fixed values of \( k \) and \( \epsilon \) were calculated at each inlet–outlet from specified turbulence intensity levels and turbulent viscosity ratios.

Grid size was typically of the order of \( 1 \, 850 \, 000 \) cells. A hybrid grid, made up of hexahedrons (typically \( 70\% \)), tetrahedrons (typically \( 29\% \)), and prisms (typically \( 1\% \)), was used. Independence of the results with respect to grid size and convergence was checked by additional simulations using a grid half as dense or performed as far as residual values six times higher. These changes did not significantly alter the air velocity profiles obtained. Simulation time for a cluster of Linux 32 bit computers was typically 530 min.

Figure 3 provides a diagrammatic representation of the coordinate system applied in the laboratory CSC simulations. Origin \( O \) is located at the front end of the workbench, just behind the front bevelled edge and against the left-hand internal wall of the cabinet. The \( x \)-axis is horizontal, perpendicular to the front opening plane, and directed outward from the cabinet. The \( y \)-axis is horizontal and parallel to the front opening plane. The \( z \)-axis is vertical and directed upward. In relation to these axes, the corresponding air velocity components are denoted \( U, V \), and \( W \), respectively. With respect to this system, the laboratory CSC has the following characteristic coordinates (in metres): horizontal spans of workbench and top filter: \( X = -0.581 \) to 0 and \( Y = 0 \) to 1.190; height of workbench: \( Z = 0 \); vertical span of cabinet front opening: \( Z = 0.022 \) (height of front edge) to \( Z = 0.222 \) (bottom of window); position of window: \( X = 0.006 \) to \( X = 0.014 \).

![Fig. 3. Vertical cross section showing coordinate axes and velocity inclination angle below the horizontal.](https://academic.oup.com/annweh/article-abstract/54/2/236/166004)
The vertically measured distance from the bottom of the front opening, non-dimensionalized by its height is denoted \( H \): the bottom of the opening therefore corresponds to \( H = 0 \) and its top corresponds to \( H = 1 \). It should be noted that air velocity components \( U \) and \( W \) are usually negative in the front opening because of the position of the suction openings at the bottom of the cabinet internal-working volume. Figure 3 also defines the angle of inclination \( \beta \) of the velocity below the horizontal plane (declination). For a constant velocity magnitude, an increase in this angle of inclination corresponds to a decrease in the velocity horizontal component (perpendicular to the opening) and thus potentially less protection for the operator.

Two independent experimental validations of the digital simulation methods were undertaken:

- A comparison of airflow profiles measured at the hospital with results of a simulation based on input data comprising the geometry of the instrumented CSC and measured airflows on site;
- A comparison of anemometric measurements in the laboratory with airflows calculated from a simulation (E) performed under non-isothermal conditions based on the geometry of the CSC studied inside the test cabin and airflows measured in the laboratory.

A further series of simulations then analysed the influence on airflows of various operating parameters around cabinet nominal characteristics for the CSC studied in the laboratory: recycled air temperature, relative values of product protection and exhaust airflow rates, spatial distribution of suction openings through the workbench, air compensation mode and draughts, operator arm inside the CSC, and disturbances due to operator presence in front of cabinet. Table 1 summarizes these simulations: airflows \( (Q) \) and discharge velocities \( (U) \) have been suffixed 1 for front opening values, 2 for recycled air supply values at the top of the effective volume, and 3 for extraction values through the workbench (Fig. 1).

Except for two simulations (F and G), all flow computations were performed based on an air compensation method involving fabric socks and no additional general ventilation of the cabin. Other compensation methods for the airflow extracted by the CSC and chamber ventilation system were studied by simulations F and G. Impacts on flows around obstructions formed by the operator’s arm inside the CSC and the operator’s body in front of the CSC were separately investigated to allow evaluation of their respective significance. The test methods described in European Standard EN-12469 (CEN, 2000) effectively take into account the possible presence of the operator’s arm, but not his body.

Table 1. Summary of digital flow simulations for CSC studied in the laboratory

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Front opening</th>
<th>Recycled air supply</th>
<th>Recycled</th>
<th>Exhaust</th>
<th>Velocity</th>
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<tr>
<td></td>
<td>( Q_1 ) ( (m^3 s^{-1}) )</td>
<td>( U_1 ) ( (m s^{-1}) )</td>
<td>( Q_2 ) ( (m^3 s^{-1}) )</td>
<td>( U_2 ) ( (m s^{-1}) )</td>
<td>( Q_2/Q_3 ) (%)</td>
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<td>0.285</td>
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<td>0.413</td>
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<td>0.373</td>
<td>0.283</td>
<td>0.409</td>
<td>76.1</td>
</tr>
<tr>
<td>D</td>
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<td>0.449</td>
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<td>0.413</td>
<td>72.8</td>
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<tr>
<td>F</td>
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<td>0.449</td>
<td>0.285</td>
<td>0.413</td>
<td>72.8</td>
</tr>
<tr>
<td>G</td>
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<td>0.449</td>
<td>0.173</td>
<td>0.250</td>
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<td>0.438</td>
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</tr>
<tr>
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<td>0.449</td>
<td>0.346</td>
<td>0.500</td>
<td>76.4</td>
</tr>
<tr>
<td>L</td>
<td>0.107</td>
<td>0.449</td>
<td>0.389</td>
<td>0.562</td>
<td>78.4</td>
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<tr>
<td>M</td>
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<td>0.449</td>
<td>0.151</td>
<td>0.218</td>
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<td>0.449</td>
<td>0.303</td>
<td>0.438</td>
<td>73.9</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

Site measurements

On the CSC studied on site, the anemometric measurements taken in the descending airflow give a mean air velocity $U_2$ of 0.31 m s$^{-1}$. Longitudinal asymmetry in supply velocities was observed between the left-hand and right-hand sides of the cabinet. This is probably related to the position of the internal air-recycling fan selected by the manufacturer. Located above the filter inside the CSC top housing, this fan is in fact installed in a highly eccentric position. Discharge velocity $U_1$ in the cabinet front opening, computed from the exhaust flow using the balometer, is 0.30 m s$^{-1}$. The exhaust–compensation flow balance indicates a room under positive pressure.

Figure 4 provides a comparison of measured values of the horizontal component of the air velocity in the cabinet front opening with values obtained for the same configuration using digitally simulated flows along two profiles: a vertical profile in the cabinet symmetry plane and a longitudinal profile at front opening mid-height. Agreement between these two sets of values is satisfactory. Longitudinal asymmetry of the product protection descending flow causes asymmetry of the experimental velocity profile along the longitudinal y-axis within the front opening, as shown in Fig. 4b.

Laboratory measurements

Under the testing cabin-operating conditions, the measurements taken on the laboratory-studied CSC lead to an exhaust airflow $Q_1$ of 320 m$^3$ h$^{-1}$ (17% less than the nominal airflow determined by the manufacturer); this corresponds to a discharge velocity in the front opening $U_1$ of 0.372 m s$^{-1}$. Unlike the cabinet studied on site, the longitudinal distribution of measured velocities is uniform over most of the front opening. The recycled airflow at the top, $Q_2$, is 1017 m$^3$ h$^{-1}$, which is within 1% of the nominal recycled airflow.

The tests also show that, under the effect of the fan motors in the CSC top housing, the air supplied at the top of the cabinet is re-introduced at a higher-than-ambient temperature. This temperature difference was 3.7 Kelvin after thermal stabilization. This corresponds to a Grashof number based on the descending flow hydraulic diameter of $266 \times 10^6$.

Figure 5 shows a comparison of the air velocities measured in the cabinet symmetry plane with values obtained for the same configuration provided by simulation E. The latter simulation was conducted under non-isothermal conditions, taking into account the air temperature rise at the cabinet top filter outlet. Two plots are shown: a vertical profile of the horizontal component $U$ of the velocity 10 mm inside the working volume ($X = -0.010$ m) and a horizontal profile of the velocity magnitude perpendicular to the front opening plane, at its mid-height (abscissa $X = 0$ corresponds to workbench front boundary). Close agreement between measured and computed air velocities can be observed.

Influence of recycled air temperature

Simulation D (Table 1) was performed at the same cabinet operating airflows as in simulation E, but under isothermal conditions and at a recycled air temperature at the top of the working volume identical to the ambient temperature. The velocity fields computed from these two simulations are essentially the same. The difference in experimentally observed temperature between the recycled and ambient air therefore has no influence on the air velocities obtained under the flow conditions considered. Other
flow simulations reported below were therefore performed under isothermal conditions.

**Airflow structure**

Simulation A1 (Table 1) corresponds to the CSC nominal operating conditions: discharge velocities through the front opening and at the top filter outlet are 0.449 and 0.413 m s\(^{-1}\), respectively, representing a 72.8\% recycled fraction of the total flow rate. Figure 6, plotted in the cabinet vertical symmetry plane, illustrates the overall flow structure. The vertical descending product protection flow delivered through the working volume top filter sweeps the interior of the CSC, then separates into two streams as it approaches the workbench. These streams flow towards the suction perforations at the front and rear of the workbench. The cabinet low-level central section features a dead zone, in which low air velocities prevail. Figure 7 shows plots of pathlines in the same vertical symmetry plane. These pathlines originate at both the high-level filter and the CSC exterior through its front opening. They terminate in the suction vents at the rear and in front of the workbench. Two of the pathlines shown in this figure play a special part. One (the third line from the left) divides the flow from the working volume ceiling into the portion extracted through the rear perforations and the portion extracted through the front perforations. This separating pathline terminates at a stagnation point on the workbench underneath the dead area referred to
above. Moreover, the pathline leaving the bottom edge of the window separates the flow from the high-level filter from the flow entering the CSC through the front opening. The latter pathline allows us to evaluate the extent of the CSC internal volume occupied by unfil-
tered air from the chamber housing the CSC.

In the cabinet front opening, air velocities are almost horizontal at low level, near the workbench, and gradually slope downward at high level, near the window. Simultaneously, the air velocity mag-
nitude decreases as the distance from the suction perforations increases. The combined effect of these two variations causes a very uneven distribution of the air velocity horizontal component \( U \), with respect to the opening height. The absolute value of this component decreases continuously from the bottom to the top of the opening.

If the front opening height is divided by thought into three identical superposed bands, then Table 2 gives the velocity components at the three heights representing the centre of the lower third \((H = 1/6)\), middle third \((H = 1/2)\), and upper third \((H = 5/6)\), at the cabinet centre, and in the vertical plane extending the window internal face \((X = 0.006 \text{ m})\). For simulation A1, broadly charac-
terized by a discharge velocity \( U_1 \) of \( 0.449 \text{ m s}^{-1} \) in the opening, the absolute value of horizontal component \( U \) is \( 0.935 \text{ m s}^{-1} \) \((208\% \text{ of } U_1)\) at centre of lower third \((H = 1/6)\), \( 0.235 \text{ m s}^{-1} \) \((52\% \text{ of } U_1)\) at centre of middle third \((H = 1/2)\), and \( 0.055 \text{ m s}^{-1} \) \((12\% \text{ of } U_1)\) at centre of upper third \((H = 5/6)\).

This vertical non-uniformity of the horizontal component \( U \) also appears in the experimental and digital profiles, which have been plotted for simulation E slightly inside the cabinet \((X = -0.010 \text{ m})\) in Fig. 5a and for the cabinet instrumented on site in Fig. 4a.

**Product protection flow**

Simulations A1 and H to N (Table 1) were performed to study the influence of the product protection airflow, introduced at the top of the working volume, on airflows within the CSC. In this series of simulations, the discharge velocity through the cabinet front opening \( U_1 \) was kept constant at the nominal value of \( 0.449 \text{ m s}^{-1} \). The supply velocity \( U_2 \) at the top filter outlet varies between \( 0.218 \) and \( 0.562 \text{ m s}^{-1} \), i.e. within a range embracing values quoted for information by European Standard EN-12469. In the front opening, the following flow variations (Table 2) are observed when the supply velocity \( U_2 \) increases:

- The air velocity vertical component \( W \) increases in absolute values over the full height of the opening. This increase is more marked towards the bottom of the opening than towards the top;
- The velocity inclination below horizontal increases over the full height of the opening. This increase in angle \( \beta \) is especially marked towards the top of the opening: when the velocity ratio \( U_2/U_1 \) increases from 0.486 to 1.253, the angle of inclination \( \beta \) increases from \( 58.8^\circ \) to \( 86.9^\circ \) at \( H = 5/6 \), but increases from \( 22.3^\circ \) to \( 33.5^\circ \) at \( H = 1/6 \);
- The vertical non-uniformity of the horizontal component \( U \) (perpendicular to the opening) increases; in absolute values, this component increases in the lower section of the opening and decreases in the upper section, thereby potentially providing less operator protection. Figure 8 shows these variations of \( U \) at three opening heights (centre of opening lower third, middle third, and top third) with respect to the velocity ratio \( U_2/U_1 \).

**Spatial distribution of suction openings**

In simulation C, the CSC operated under airflows identical to those used in simulation A1, but the air extraction system at the bottom of the

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**Table 2. Influence of velocity ratio \( U_2/U_1 \) on air velocities in the vertical symmetry plane of front opening**

<table>
<thead>
<tr>
<th>Velocity ratio ( U_2/U_1 )</th>
<th>( H = 1/6 )</th>
<th>( H = 1/2 )</th>
<th>( H = 5/6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( U (\text{m s}^{-1}) )</td>
<td>( W (\text{m s}^{-1}) )</td>
<td>( \beta (^\circ) )</td>
</tr>
<tr>
<td>0.486</td>
<td>N</td>
<td>-0.807</td>
<td>-0.331</td>
</tr>
<tr>
<td>0.557</td>
<td>H</td>
<td>-0.828</td>
<td>-0.363</td>
</tr>
<tr>
<td>0.696</td>
<td>I</td>
<td>-0.871</td>
<td>-0.425</td>
</tr>
<tr>
<td>0.834</td>
<td>J</td>
<td>-0.912</td>
<td>-0.487</td>
</tr>
<tr>
<td>0.920</td>
<td>A1</td>
<td>-0.935</td>
<td>-0.524</td>
</tr>
<tr>
<td>0.976</td>
<td>K</td>
<td>-0.950</td>
<td>-0.549</td>
</tr>
<tr>
<td>1.115</td>
<td>L</td>
<td>-0.984</td>
<td>-0.610</td>
</tr>
<tr>
<td>1.253</td>
<td>M</td>
<td>-1.013</td>
<td>-0.670</td>
</tr>
</tbody>
</table>
effective volume, comprising two sets of slots (at front and rear of cabinet), was replaced by extraction through a fully perforated workbench. The extraction area was therefore increased from 0.15 to 0.69 m².

This modification results in disappearance of the dead area near the workbench inside the CSC. It also creates a less unbalanced vertical distribution of the horizontal air velocity component $U$ in the cabinet front opening and thereby potentially provides better operator protection. For example, in the vertical symmetry plane, switching from configuration A1 to configuration C results in the absolute value of $U$ decreasing from 0.935 to 0.693 m s⁻¹ at $H = 1/6$ and increasing from 0.055 to 0.230 m s⁻¹ at $H = 5/6$. However, at the same time, the ambient air in the room containing the CSC, which is drawn into the front opening, penetrates deeper into the cabinet; this is shown by the pathlines plotted from the bottom edge of the window in Fig. 9. The air drawn into the CSC from the room has not been subjected to high-efficiency filtration, so this greater cabinet penetration depth may adversely affect product protection under certain conditions.

Air compensation mode and draughts

Simulations F and G made it possible to investigate the influence of cabin air compensation mode and vertical draughts (Table 1). In simulation F, compensation was no longer performed by fabric socks but using the cabin central plenum, which was located directly above the CSC. The plenum had no louvres and blew the compensation air vertically. Simulation G included an additional cabin general ventilation flow through the two freestanding units, which pulled out three times the airflow extracted by the cabinet. The air change per hour was thereby increased from 6.4 in simulations A1 and F to 25.6 in simulation G. The face velocity at the plenum opening was 0.040 m s⁻¹ in simulation F and 0.161 m s⁻¹ in simulation G.

Within the scope of the studied configurations, the results show that values of the air velocity horizontal component in the front opening plane are very little affected by these changes in compensation mode. The velocity inclination below the horizontal increases slightly towards the mid-height of the front opening, when switching from configuration A1 to configuration F and then to configuration G. For example, angle $\beta$ in the symmetry plane at the opening mid-height increases from 60.5° in configuration A1 to 61.6° in configuration F and to 64.3° in configuration G.

Operator arm penetration

Simulation B was performed by inserting into the airflow an obstruction representing the operator’s arm penetrating inside a CSC. The arm is modelled in the same way as in the testing method described in Appendix C of European Standard EN-12469 (CEN, 2000) by placing a closed horizontal cylinder at the centre of the cabinet. One end of this cylinder touches the back of the CSC and the other projects 150 mm into the room through the cabinet access opening. The cylinder diameter was 64 mm and its longitudinal axis was located 69 mm above the workbench.

The results show that flow disturbances remain limited in the immediate vicinity of the cylinder. The descending flow bypasses the obstruction.
Operator presence in front of cabinet

Simulation P was performed to study the influence on the airflows of an operator sitting in a working position at the centre of the CSC. An obstruction with rounded vertical front and top edges was positioned in front of the cabinet to model the operator’s legs and trunk up to the shoulders. The trunk width (along y-axis) was 0.420 m and its thickness (along x-axis) was 0.260 m.

The computation results reveal a wake, downstream of the obstruction, between the operator and the cabinet front opening. Figure 11 shows air velocities in the horizontal plane at opening mid-height. However, the wake remains limited in size. Air converges from the obstruction lateral edges towards the opening centre and no airflow is observed to leave the cabinet. Operator presence causes a loss (in absolute values) of horizontal velocity component $U$ of the air velocity in the opening central section. This loss is highlighted in Fig. 12, which compares the longitudinal profiles of velocity component $U$ at the opening mid-height. These profiles were plotted for identical airflows in configuration A1, without an operator, and in configuration P, with an operator. For the simulated configuration, the decrease in $U$ in the symmetry plane due to operator presence in front of the cabinet reaches 21% at 1/6 of the opening height, 25% at mid-height, and 33% at 5/6 of the opening height. This decrease lowers the operator protection level ensured by the CSC in relation to risks of pollution leakage.

CONCLUSION

This study investigated the specific fluid dynamics characteristics of CSC, particularly those used in cancer drug reconstitution operations. Measurements taken on site were used to derive characteristic data for these cabinets. An in-depth laboratory investigation of airflows inside another CSC was also conducted. Anemometric values recorded on these two installations enabled the experimental validation of computational fluid dynamics methods applied to CSC. The digital flow simulations conducted provide a better grasp of the detailed flow structure inside a CSC and made it possible to study the influence of different operating parameters on the air velocity distribution inside the cabinet front opening.
At constant discharge velocity through the front opening, an increase in the recycled product protection air supply velocity at the top of the cabinet causes greater inclination of air velocities below the horizontal and accentuates vertical non-uniformity of the horizontal velocity component. Switching from a workbench incorporating rows of perforations at front and rear to a workbench extracting air over its entire surface leads to a more uniform vertical distribution of the velocity horizontal component in the opening but simultaneously to deeper penetration inside the CSC of unfiltered air drawn in from the room housing the cabinet.

Within the scope of the studied configurations, the simulations performed also reveal that the product protection air temperature, the mode of compensating the air extracted by the cabinet and the presence of moderate vertical draughts or of an operator arm inside the cabinet have little effect on the air velocities in the front opening. On the other hand, an operator in working position in front of the CSC causes a reduction in the horizontal component of the velocity in the opening section facing the operator.

Unlike standardized testing methods based on using particulate tracers, which provide only an overall indication of CSC performance, the experimental and digital methods applied in this study allow a better understanding of the detailed structure of airflows inside a CSC. In particular, these methods show that a safety cabinet, usually characterized by a mean velocity in its front opening, really does feature a highly non-uniform distribution of the air velocity horizontal component, with respect to height in the opening. Specifically, the opening upper section is where low values of this velocity horizontal component occur. These methods also show the antinomic effects of certain cabinet design parameters, such as product protection airflow or spatial distribution of the suction openings through the workbench, on both product and operator protection.

Nomenclature of main symbols used

$H$ (-): non-dimensional height in front opening
$Q_1$ (m$^3$ s$^{-1}$): safety cabinet exhaust airflow
$Q_2$ (m$^3$ s$^{-1}$): product protection airflow
$Q_3$ (m$^3$ s$^{-1}$): total extracted airflow through workbench

$U_1$ (m s$^{-1}$): horizontal discharge velocity through opening
$U_2$ (m s$^{-1}$): vertical discharge velocity at top filter outlet
$U, V, W$ (m s$^{-1}$): velocity components along $x$-, $y$- and $z$-axes
$X, Y, Z$ (m): Cartesian coordinates
$\beta$ (degrees): air velocity inclination below horizontal

REFERENCES


