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Numerical Simulation and Ventilation Efficiency of Bicycle Helmets

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Abstract: This paper demonstrates the use of the concept of the local mean age of air (LMAA) to quantify ventilation effectiveness under bicycle rider's safety helmets. The specific objective is to study the effect of helmet openings on the resulting ventilation effectiveness. To quantify ventilation effectiveness using the concept of LMAA, dynamic tracer gas data are necessary. The data were generated using a Computational Fluid Dynamics (CFD) model. Two bicycle helmet designs were used and compared with respect to ventilation performance. The result showed that the helmet with more openings had better performance especially at the back of the head. The methodology has practical importance in order to integrate riders comfort criteria in the design of new helmets.

Keyword: helmet; CFD; Ventilation

1 Introduction

Every year, many cyclists die as a consequence of an unfortunate tumble or a traffic accident in which they suffer from a severe head injury. It is estimated that most of these head injuries could be avoided or significantly reduced by wearing a cyclist safety helmet (Burke, 1988). However, a lot of cyclists still do not like to wear a safety helmet because of the thermal discomfort that comes with it, especially in the summer time when cycling is popular (Wardle and Iqbal, 1998) and environmental temperature is high.

The human head plays an important role in the thermal regulation of the body. Up to 50% of the produced latent and sensible heat can be dissipated to the surrounding via the head, causing high temperatures build up and sweat production on the head (Rasch, Samson, Cote and Cabanac, 1991). Researches have revealed that, on whole body scale, the amount of sweat production differs from body part to body part (Johnson, Scott, Coyne, Sahota, Benjamin, Rhea, Martel and Dooly, 1997) and that the distribution of the total amount of latent heat losses changes with changing effort level and environmental conditions (Desruelle and Candas, 2000).

Helmet manufacturers are aware of this problem and have taken it into account in the product requirements of their new designs. As a result, bicycle helmet design has a trend towards more open structures, making it necessary to use materials with a higher stiffness in order to maintain the mechanical strength of the helmet (Ellis, Bertolini and Thompson, 2000). Bicycle helmets constructed from isotropic materials with higher stiffness provide less damping resulting in fatal injuries during accidents. Therefore there is a need to reconsider the effectiveness of open helmets. Despite the abundance of reports on the injury assessment of bicycle related accidents in relation to mechanical strength of safety helmets, there have been few researches conducted to address ventilation efficiency of helmets and thermal comfort of cyclists. Van Brecht, Nuyttens, Aerts, Quanten, De Bruyne and Berckmans (2007) used a Data Based Mechanistic (DBM) model to assess ventilation performance of an existing cyclist helmet. The experimental set up was a manikin wearing a helmet which was subjected to controlled ventilation. The model parameters were identified statistically from sets of data obtained from dynamic tracer gas experiments. Carbon dioxide was used as a tracer gas. The authors showed that the first order parameter of the model

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has a physical meaning. This model parameter was used to quantify ventilation performance at pre-selected sampling positions on different parts of the manikin's head. The conclusion of the research was that ventilation efficiency of the helmet is dependent on the position of the sampling point and the angle of inclination of the manikin with respect to the incoming air.

This paper outlines a methodology that can be used to quantify ventilation performance of helmets which can lead to thermally comfortable new designs. The method uses the concept of the LMAA. The concept is used to quantify ventilation effectiveness and to compare ventilation strategies in indoor air studies (Desta, Van Buggenhout, Van Brecht, Meyers, Aerts, Baelmans and Berckmans, 2004).

The LMAA is defined as the average time spent for all air particles introduced at the inlet of a volume to reach a particular point in the flow domain. The smaller the LMAA the better the ventilation is performing for that local position. In practice, this quantification of LMAA necessitates availability of dynamic input-output tracer gas data.

The required data is often obtained by performing experiments on manikins and human subjects. However experiments can be expensive and time consuming. Alternatively, Computational Fluid Dynamics (CFD) can be used to supplement experiments. The method is a cheap way of generating data and provides detailed flow field distributions of temperature, pressure and species concentrations (Fujimoto and Nishioka, 2006; Nicolas and Bermudez, 2007).

The objective of this study was to develop a methodology for quantification of ventilation performance of bicycle helmets. The methodology used CFD methods to generate tracer gas data. Contrary to many CFD reports in the literature, the presented model incorporates the geometric complexity of bicycle helmets accurately.

In order to investigate the effect of the number of helmet openings on the resulting ventilation effectiveness, two helmet designs were considered.

2 Material and methods

A full scale ventilated cylindrical chamber with a manikin head and helmet is used to elaborate a methodology that can quantify ventilation effectiveness of helmets. The geometric model of this set up and the geometric features of the considered two helmets are explained in section 2.1. In section 2.2 the CFD tracer gas data generation procedure, which is essential for ventilation effectiveness analysis is depicted. In section 2.2 the theoretical basis of the local mean age of is highlighted. In section 3.1 and 3.2 results of the CFD simulation and the LMAA analysis of the two helmets are discussed respectively. In section 4 conclusions are provided.

2.1 The test configurations

The studied numerical set up was a full scale ventilated cylinder with a length of 1.658m and diameter of 1.170m. The volume of the flow domain is 1.7826m^3. The cylinder has an air inlet and an outlet at the left and right hand side respectively. Inside the cylinder a manikin head with a helmet is placed. The distance between the centroid of the head and the inlet is 0.772m. The gap between the centroid of the head and the top of the cylinder is 0.644m (fig. 1).

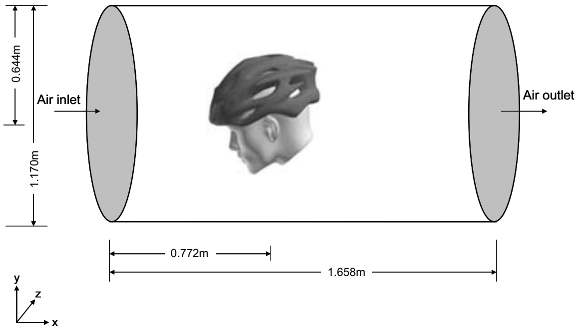

Figure 1: The ventilated test set up

For the study, a commercially available standard helmet was used (fig. 2). The helmet was the successor of the helmet that was identified as a "best buy" by the Belgian consumer organisation "Test-Aankoop" in 2005. The head geometry was derived from a manikin head with a circumference of 590 mm.

A 3D laser scanner, Metris Modelmaker D, was used to capture point cloud of the helmets surface and the manikin head. This point cloud was exported as a surface mesh and modified using 3-Matic software. Modification of the surface mesh allows control over optimisation of the regularity (skewness) of the elements. Then a tetrahedral volume mesh was created in the space between head, helmet and cylinder using T-Grid from the optimised surface mesh.

The effect of the helmet openings on ventilation effectiveness was studied by modifying the standard helmet. As suggested by Ellis, Bertolini and Thompson, (2000), openings should be positioned in areas with high static pressure. Therefore the front inlet is left open while the side openings were sealed. The outlets which are situated at the back of the helmet were left as that of the standard one (fig. 3).

The emphasis of this study is to introduce a methodology that can quantify ventilation effectiveness of bicycle helmets. The approach is described by examining an extreme hypothesis, i.e., closing all inlets of standard helmet except one, in an area of high static pressure, would result in a design with a minimum openings while providing acceptable ventilation.

Figure 2: The standard helmet configurations

As it can be seen from fig. 2 and fig. 3, on the modified helmet all the top and side openings are closed except the front inlet.

2.2 *CFD modelling*

CFD modelling is the process of representing a fluid flow problem by mathematical equations based on the fundamental laws of physics, and solving those equations at many points in space to predict the variation of relevant parameters within the flow field. Usually these will be fluid velocity, pressure and temperature, and other variables such as turbulence parameters and concentrations of chemical species (Versteeg and Malalasekera, 1995).

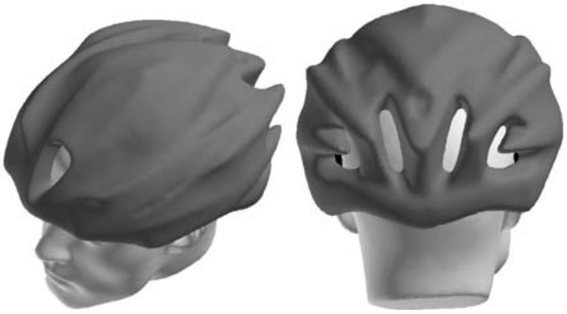

Figure 3: The modified helmet configurations

CFD models for isothermal conditions are based on conservation equations of mass and momentum. Solving these equations results in the velocity and pressure prediction throughout the flow field. If the flow is turbulent then either a turbulence model must be used which will involve solving further ensemble averaged equations, or assumptions must be made about the magnitude of the diffusion effects brought about by the turbulence. The solution of an additional equation must be obtained for each variable to be calculated. For example, additional variables could be those representing the concentration of tracer gases.

These equations, representing the conservation of mass, momentum, energy, etc., are known as field equations; they represent the variation of solution variables in space and time. They are of partial differential form and, in the mathematical sense, are highly non-linear and cannot be solved analytically except in very simplified cases which are of limited practical use. The use of numerical methods is inevitable and therefore the calculation of a flow problem requires the discretisation of that flow field in relation to space and time.

In other words the approach within CFD is to represent the equations in numerical form, linearise the equations and then solve them using numerical analysis techniques that implement iterative procedures (Soares and Vinagre, 2008; Mariani, Alonso and Peters, 2008).

The solution of partial differential equations in general and of CFD computations in particular necessitates declaration of boundary conditions at the inlets, walls, outlets and source terms. Field values at internal nodes are calculated by the model itself. Details about the governing equations, discretisation schemes and turbulence modelling can be found in standard books (e.g., Ferziger and Peric, 1999).

In practices CFD models are demonstrated to be useful for engineering applications (Yin, Rothenburg and Dusseault, 2007; Han, Feng and Owen, 2007).

In the presented research, Fluent, one of the most widely used commercial CFD codes, has been used to solve the 3D transport equations. GAMBIT and Tgrid were used to generate and optimise the volume grid from the surface mesh created by the 3Matic software. The flow domain is partitioned into 754,878 unstructured 3D cells. In fig. 4 the surface mesh is shown. The internal grid is very dense making the visibility of the head and the helmet opaque, therefore it is not displayed in the figure.

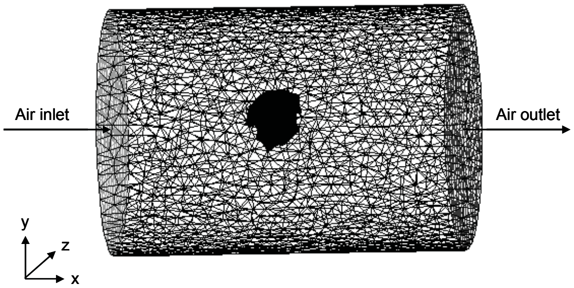

Figure 4: The surface mesh of the flow domain

As described in section 1, the ventilation effectiveness quantification using the LMAA concept necessitates the availability of informative (dynamic) tracer gas data. Hence tracer gas transport phenomena were simulated in order to generate the required data. The thermo-physical properties of the tracer gas are the same as that of the carrier gas, air, avoiding the occurrence of buoyancy effects.

For the simulation an arbitrarily chosen, but realistic constant mean air velocity of 3 m/s, normal to the inlet was used while the other components of the velocity were set to zero.

First a steady state run was conducted by setting mass fraction of the tracer gas to zero. A transient run was started from the converged steady state solution. At this transient run, the mass fraction of the tracer gas was stepped up to one at the inlet. Across the outlet zero differential pressure boundary was set. At the walls no slip boundary conditions were defined.

Eight hundred time steps of one second were simulated. For each time step 60 internal iterations were found to be adequate for a mass convergence criterion of 10-6 kg/s. Turbulence was modelled with the Spalart-Allmaras model which is recommended for externally dominated flow (Spalart and Allmaras, 1994). All equations were discretised with second order upwind scheme.

Forty monitoring positions were selected systematically on four planes covering most part of the head. In the selection, symmetry of the head was considered. The zx unwrapped view of the monitoring positions, with the manikin head as background, is shown in fig. 5. Moreover the side view of monitoring positions 1 to 10 are shown for the two helmet designs in fig. 6.

2.3 The concept of the LMAA

The concept of the LMAA, originally introduced to quantify ventilation performance for indoor air systems (Etheridge and Sandberg, 1996) can be adapted for the current application.

The particles of fresh air coming from outside arrives at a given location *i*on the cyclist head after a time τ_i which, will vary, from one particle to the other. τ_i is called the residence time of the particle or its ‘age’. Since there are a large number of particles, it is possible to define a probability density that the age of the particles arriving at a given location is between τ and $d\tau$ and a probability $F(\tau_i)$ that this age is less than τ. The following relationships always hold between these two

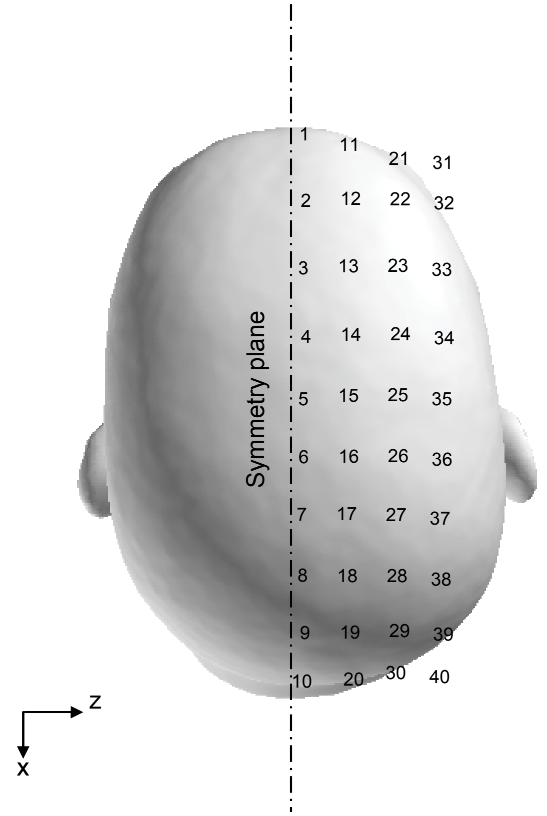

Figure 5: Top unwrapped view of the monitoring positions

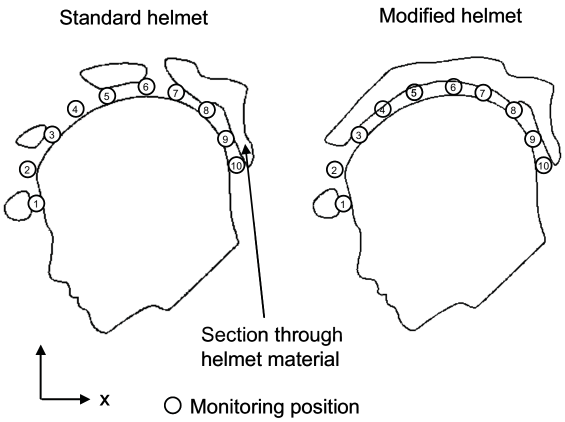

Figure 6: Side view of monitoring positions 1 to 10 at the symmetric plane

functions (Sutcliffe, 1990).

$$\frac{dF}{d\tau} = f(\tau) \quad \text{and} \quad \int_0^{\tau} f(t_i)dt = F(\tau_i) \tag{1}$$

The LMAA at point$i$ on the head is defined by the average age of all the particles arriving at that point.

$$\overline{\tau}_i = \int_0^{\infty} t f(t_i)dt \tag{2}$$

The detailed derivation of the above equations can be found in (Sutcliffe, 1990).

The knowledge of the LMAA is of great importance since it is shown that from this parameter ventilation efficiency can be quantified (Etheridge and Sandberg, 1996).

The LMAA, eq. (2) can be solved by recording the time history of a tracer gas concentration at a particular point generated by either of three tracer gas injection strategies: step injection, pulse injection and decay after uniform concentration (Roulet and Vandaele, 1991).

For step injection at the inlet the LMAA at a particular point can be quantified as (Sandberg and Sjöberg, 1983):

$$\overline{\tau}_i = \int_0^{\infty} \left(1 - \frac{c_i(t)}{c_i(\infty)}\right) \tag{3}$$

where $\overline{\tau}_i$ is LMAA [s]; t is time [s]; c_i is tracer gas concentration at point i [kg/kg].

For the presented work, eq. (3) was solved by Simpson's numerical integration rule (Kreyszig, 1993) using the time series data generated by CFD.

3 Results and discussions

3.1 The CFD simulations

Fig. 7 shows fairly complex flow phenomena under and around the helmet which are characterised by recirculation and flow separation. The flow field for the two helmet configurations has similar profiles except at the regions where the helmet holes are sealed. Moreover the upper bound of the velocity magnitude for the modified helmet is slightly higher than the standard one.

Fig. 8 shows the input output response for the standard and modified helmets at two monitoring

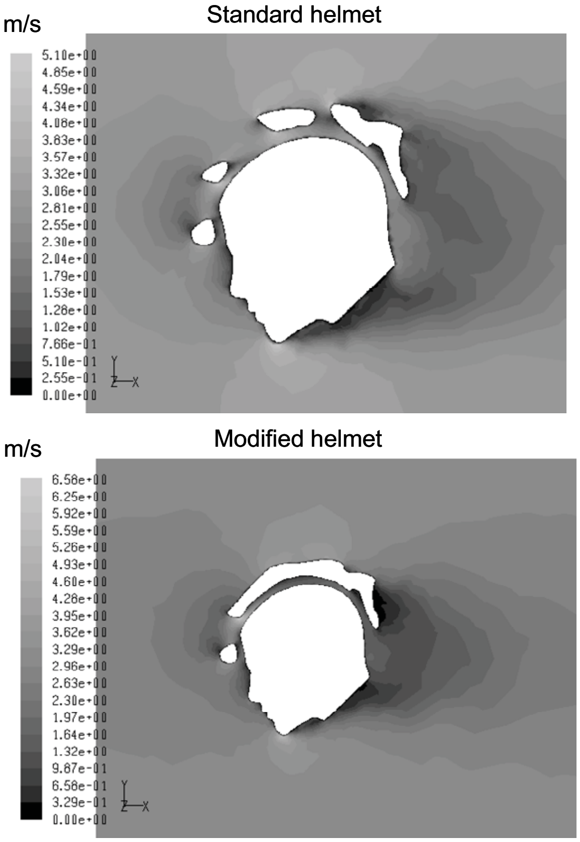

Figure 7: Steady state velocity distribution for the standard and modified helmets at the symmetry plane

positions. In the figure the response for the two helmets at position 1 is almost identical. In contrast, at position 10 significant differences, which was as high as 0.49 kg/kg at time step 355 could be observed between the responses of the two helmets. The reason for this discrepancy is the relative placement of the two positions. Position 1 is located just near the front opening of the standard helmet, in which the effect of the other openings on the position's response is negligible. This opening was not closed on the modified helmet; therefore the response at this particular position was almost identical for the two helmets. However, position 10 was located at the back of the head where the response is influenced not only by the front opening but also by the other openings too. Since some of the openings were sealed on the modified helmet, it is expected that it needed more time to reach steady state which is instigated by high time delay of the response (145s) compared to the time delay of the same position when the standard helmet is used (135s).

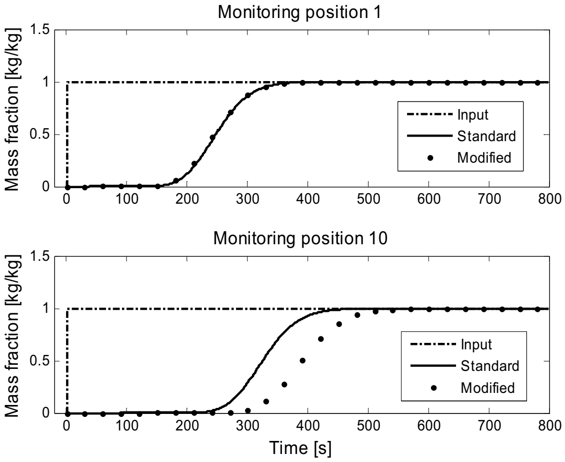

Figure 8: Input-output tracer gas concentration profile for the two helmet configuration

Fig. 9 shows the time constant distribution of the tracer gas response for the considered monitoring positions (top unwrapped view). In the figure monitoring positions 1, 10, 31 and 40 are shown. The time constant of a dynamic system is the time required to reach 63% of the new steady state value. A lower time constant is an indication of fast dynamics and the reverse is true for a higher time constant. In the figure only four monitoring positions are shown. The other positions which are shown in fig. 5 are not displayed in order to preserve the contours clarity.

For both helmets fast dynamics were observed on the upper half of the head, this is caused by the proximity of these positions to the air inlets. The fastest dynamics for the standard and modified helmets were at position 2 with time constants of 254s and 253s respectively. The mean time constant for the standard and modified helmets were 297s and 315s respectively, demonstrating faster process dynamics in the former case.

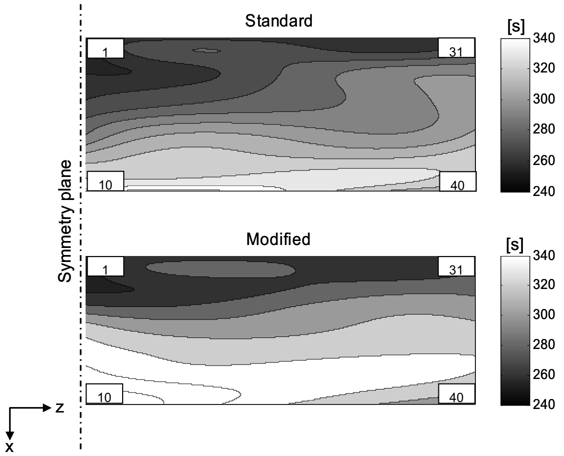

Figure 9: Contour plot of time constant (top unwrapped view)

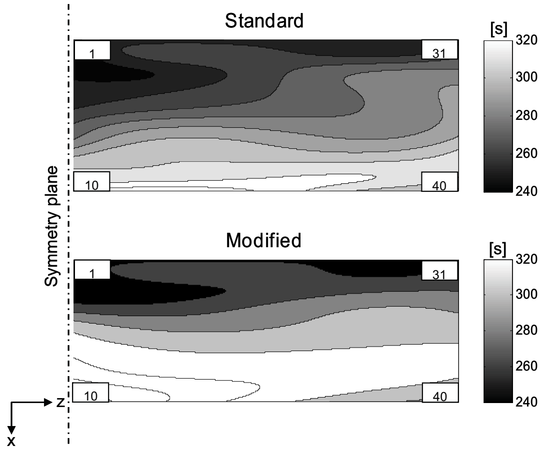

Figure 10: Contour plot of the LMAA (top unwrapped view)

3.2 *Results and discussions of the LMAA analysis*

Fig. 10 has similar profile as that of fig. 9. The figure demonstrates that the air which is coming from outside drift to the side and back of the head. The LMAA distributions in fig 10 can be categorised into two parts. The front half of the head where improved ventilation is observes with monitoring positions 1, 2, 3, 4, 5, 11, 12, 13, 14, 15, 21, 22, 23, 24, 25, 31, 32, 33, 34, 35 and the back of the head where the ventilation is relatively poor with the remaining twenty positions (positions 6, 7, 8, 9, 10, 16, 17, 18, 19, 20, 26, 27, 28, 29, 30, 36, 37, 38, 39, 40).

The average LMAA values at the front and back of the head with the standard helmet were 264s and 303s respectively. While with the modified helmet LMAA values of 272s and 331s were obtained at the front and back of the head respectively. However given the number of helmet openings sealed in the modified helmet, the obtained improvement in average LMAA by introducing more openings in the standard helmet is not significant. Therefore closing some of them, if not all, may allow using less stiff materials while keeping acceptable limits of ventilation efficiency (LMAA) under the helmet.

The presented methodology which uses dynamic tracer gas simulations to quantify ventilation efficiency of bicycle helmets is a tool that enhances a designer's insight in the cooling effect of vents during the design phase of helmets.

The simulations are based on experimental set up used by Van Brecht; Nuyttens; Aerts; Quanten; De Bruyne and Berckmans (2007). Numerical simulations are, as described by Brühwiler (2006), required to analyse bicycle helmet ventilation since the complexity of helmet geometry is taken into account. These simulations are therefore a fundamental new step in the quantification and optimization of ventilation characteristics under bicycle helmets.

The presented methodology lends a hand for a designer to come up with thermally comfortable bicycle helmets. However it is necessary to conduct wind tunnel experiments during practical implementation of the approach to assess the accuracy of the numerical model and to fine tune (optimize) key parameters of the proposed design.

4 Conclusions

In this paper a methodology is introduced to assess ventilation performance over a cyclist head with a helmet. Two helmets that differ in the number of openings are used for the study. For the analysis, dynamic tracer gas data is generated using CFD. From the ventilation effectiveness point of view, the standard helmet which has more openings shows better performance especially at the back of the cyclist head. However in the front half of the head ventilation performance is not significantly improved.

For the studied forty monitoring positions, LMAA values ranging from 241s to 339s is obtained when the standard helmet was used. Whereas with the modified helmet the range was between 239s and 393s.

The developed methodology has practical importance in order to compromise between the need of helmets that are constructed from less stiff material, which is essential for dumping effects during accidents and thermal comfort of a cyclist that has a positive influence on the willingness of riders to wear safety helmets.

The use of CFD to generate the data is useful especially when conducting experiments is not possible, such as in the early design stage of helmets.

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