Solar radiation resistance simulation of tents

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Abstract
Decathlon leads a thermal digital project with several aims. The present study is focused on the first objective, reproducing the existing physical thermal tests of tents. Therefore a great importance is attributed to the methodology to reproduce an experimental test (virtual test approach), ergo simulate the capacity of blocking solar radiation in a tent measuring principally the internal tent's temperature and the surface's irradiation. Several schemas and images are used to illustrate as clearly as possible the study case, from the context to the execution of the multi-physics analysis passing through the thermal phenomena and boundary conditions explanations. The model is firstly evaluated considering one specific model of tent (2 SECONDS EASY -2 places- Fresh & Black) and a numerical/experimental comparison is presented for validation. At this stage of the project and under the mentioned conditions, the numerical model is validated. Nevertheless, to fully claim reliability of the model, more tents must be numerically tested and validated.

Keywords: dry-bulb temperature, surface irradiation, Fresh & Black technology.

Introduction
High temperature variations inside a tent can be a real problem for campers' thermal comfort. In fact, a difference going up to 15 °C between the temperature of the air at the high parts of a tent and the ambient external temperature, has been measured [1].

Furthermore, the most desired and frequent environment to use a tent is when the weather is mild, this means temperatures between 64 and 86 degrees Fahrenheit (18 and 30 degrees Celsius) and less than 0.04 inches (1 mm) of rain [2]. Even when these temperatures are reached, depending on the locations (altitude, air pressure, vapor content, etc.), the conditions can fastly change at night and then, a decrease of the temperature is notably remarqued. As a result, campers aim for thermally comfortable tents and by this they mean, an equipment that can assure the same or a fresher temperature of the external environment when the temperature is hot enough, from 23 °C to 30 °C or even higher temperatures and at the same time, they want higher temperatures at the interior of the tent when it is cold outside (less than 18 °C).

To increase user comfort especially in hot days and in the sunrise, Decathlon has developed tents called "Fresh & Black (F&B)" [1]. The main improvement of this equipment lies in the textile technology [3], which regulates the temperature inside and reduces the interior surface irradiation compared to classic textiles used in similar applications. In addition to the thermal isolation properties, these kinds of tents provide a better sleep quality for the user. To quantify the performance of a tent reflecting and absorbing the solar radiation, laboratory tests are conducted.

Today, testing the tents in this external lab is the only way of comparing the performance of different prototypes regarding temperature and solar radiation resistance. This procedure is expensive, time consuming and needs reliable prototypes that are made iteratively.

That is why; Decathlon leads a thermal simulation project that firstly aims to reproduce the experimental tests. Then, to compare tents efficiently in order to reduce the prototype's iterations. Furthermore, to create a simulation application as a predictive tool. This simulation application will allow us to rapidly test different materials and to optimize the design (geometry, aeration, etc.) considering thermal efficiency and eco-design. In summary, the numerical approach will definitely contribute to decreasing financial means and saving time.

Experimental & Simulation Set Up
A partner laboratory with the needed facilities performs the test with specific conditions (inspired from the international standard ISO 7243), having as objective to verify the capacity of blocking solar radiation in a tent (c.f. Figure 1).

Figure 1. Example of an experimental test conducted during summer 2024, tent model: Arpenaz 4.1.

Thermal Phenomena

The sun lighting produced by the lab's solar ramp represents a typical summer day. Wind's speed and solar radiation's power are controlled to imitate particular conditions (extreme, critical or aggressive conditions are often preferred to test the worst case scenario). For this matter and to create a mixed convection, temperature and humidity of the test area must be stable, controlled and fixed to (27 ± 2) °C and (60 ± 5) % H.R, respectively. Wind speed should be set to (2 ± 0.5) m/s and an homogeneous field in all the tent surface shall be guaranteed.

Radiative flow must also be stable, controlled and adjusted to have 750 W/m² ± 50 W/m² measured at ground level in the test zone and within the solar spectrum. To assure so, the solar ramp at the ceiling is composed of 10 lines of 6 lamps spaced 50 cm and fixed at a variable height following the aging of the lamps (natural loss of power). The spots' orientation allows the radiation to be concentrated in a zone of 2 m by 4 m (c.f. Figure 2). The surface radiation is measured in 5 points before the tests and considering an empty chamber.

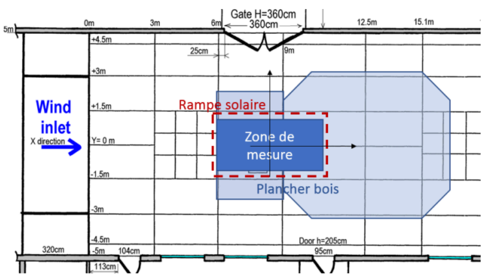

Figure 2. Schema of the lab's facilities, illustrating the solar ramp, the wooden floor and the measurement zone.

Considered Physics & Multiphysics

To correctly reproduce the experimental tests, using the COMSOL's Heat Transfer Module and the Fluid Flow Module rapidly became a good solution because of the multiphysics occurring in this problem.

The model is defined using two multiphysics: a Nonisothermal Flow and a Heat Transfer with Surface-to-Surface Radiation. This means that three physics are taken into account: Flow, Heat transfer in Fluids and Surface-to-Surface Radiation (c.f. Figure 3).

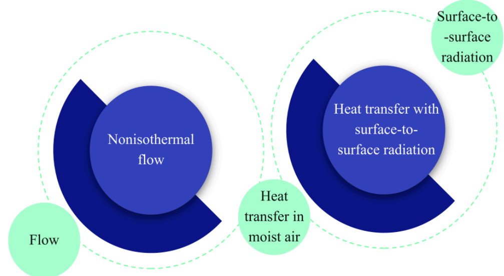

Figure 3. Schema of the physics and multiphysics used to solve the case study.

To numerically simulate the lab's solar ramp, one single spot was created as an external radiation source respecting a certain height (4 m from the floor -default distance used at the lab-) and placed at the center of the chamber representation. An auxiliary sweep was used to find the power value of the single spot that actually represents the concentrated and equivalent power of the 60 spots. As in the experimental test, the surface radiation is numerically measured in 5 points before any test and considering an empty chamber (c.f. Figure 4).

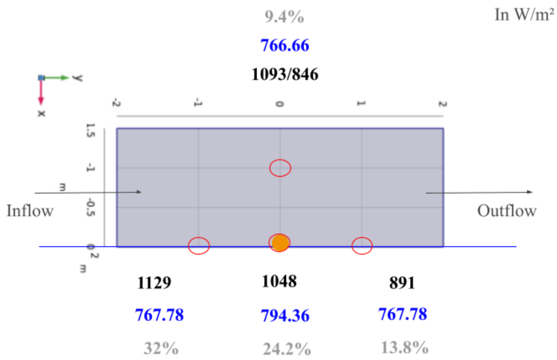

Figure 4. Schema of the virtual measurements of surface irradiation to calibrate the model respecting the experimental thresholds from the standard. Numbers in black represent the lab results, in blue the numerical results and in gray the difference between them.

Numerical Model & Methods

To be able to choose the right flow regime, the Reynolds number was calculated (c.f. Equation 1). As a reminder, this number represents the ratio between inertial and viscous forces. At low Reynolds numbers, viscous forces dominate and tend to damp out all disturbances, which leads to laminar flow. At high Reynolds numbers, the damping in the system is very low, giving small disturbances the possibility to grow by nonlinear interactions. If the Reynolds number is high enough, the flow field eventually ends up in a chaotic state called turbulence [4].

$$R_e = \frac{\rho U L}{\mu} \quad (1)$$

As the Reynolds number is around the magnitude of $x10^5$. The flow is definitely turbulent for this application.

Only 4 different types of RANS turbulence models are available within our license. As a result and in order to solve the model, three stationary studies are considered (c.f. Figure 5):

1. The first one, using a k-ε turbulence model with wall functions treatment.
2. The second one, implementing a Low Reynolds number k-ε turbulence model with an Automatic wall treatment and

considering the initial values of variables solved from the first study.

3. The third one, using the Ray shooting method as a radiation method and considering the values of variables not solved from the second study.

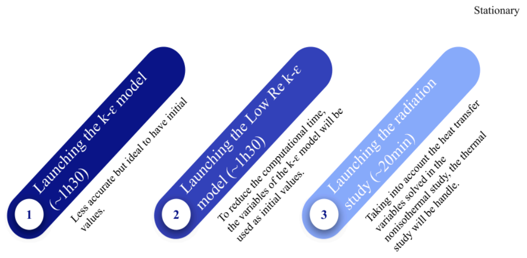

Figure 5. Methodology considered to treat the multiphysics approach.

Governing Equations

The equations solved by the Turbulent Flow, Low Re k-ε interface are the Reynolds-averaged Navier-Stokes (RANS) equations for conservation of momentum and the continuity equation for conservation of mass (c.f. Equations 2). Turbulence effects are modeled using the AKN two-equation k-ε model with realizability constraints. The AKN model is a so-called low-Reynolds number model, which means that it can resolve the flow all the way down to the wall. The AKN model depends on the distance to the closest wall. The physics interface therefore includes a wall distance equation [4].

$$\rho\frac{\delta k}{\delta t} + \rho u\cdot\nabla k = \nabla\cdot\left(\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right) + P_k - \rho\varepsilon \qquad (2)$$
$$\rho\frac{\delta \varepsilon}{\delta t} + \rho u\cdot\nabla \varepsilon = \nabla\cdot\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla \varepsilon\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - f_\varepsilon C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}$$

Where

$$P_k = \mu_T\left(\nabla u:\left(\nabla u + (\nabla u)^T\right) - \frac{2}{3}(\nabla\cdot u)^2\right) - \frac{2}{3}\rho k\nabla\cdot u$$
$$\mu_T = \rho f_\mu C_\mu \frac{k^2}{\varepsilon}$$
$$f_\mu = \left(1 - e^{-l^*/14}\right)^2\cdot\left(1 + \frac{5}{R_t^{3/4}}e^{-\left(R_t/200\right)^2}\right)$$
$$f_\varepsilon = \left(1 - e^{-l^*/3.1}\right)^2\cdot\left(1 - 0.3e^{-\left(R_t/6.5\right)^2}\right)$$
$$l^* = \left(\rho u_\varepsilon l_w\right)/\mu \quad R_t = \rho k^2/(\mu\varepsilon) \quad u_\varepsilon = (\mu\varepsilon/\rho)^{1/4}$$

and

$C_{\varepsilon 1} = 1.5$ $\qquad C_{\varepsilon 2} = 1.9$ $\qquad C_\mu = 0.09$

$\sigma_k = 1.4$ $\qquad \sigma_\varepsilon = 1.4$

l_w is the distance to the closest wall.
u is the velocity field and its components.
ρ is the pressure.
k is the turbulent kinetic energy
ε is the turbulent dissipation rate
μ is the dynamic viscosity

For the briefness of this section, specific equations used to solve the Automatic Wall Treatment are not explicit hereby but can be found in literature as well as the model parameters unspecified above [4].

The Heat Transfer with Surface-to-Surface Radiation multiphysics coupling assumes a weak coupling between temperature and radiosity variables solved by a Heat Transfer interface and a Surface-to-Surface Radiation interface, respectively. The default solver contains dedicated segregated groups for temperature and radiosity variables. The Heat Transfer in Fluids solves the following equation (c.f. Equation 3):

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\cdot\nabla T\right) + \nabla\cdot(q + q_r) = \alpha_p T\left(\frac{\partial p}{\partial t} + u\cdot\nabla p\right) + \tau:\nabla u + Q \qquad (3)$$

Details and the sequel of calculations can be found in literature [5]. Hence, when running the radiation study, three important variables are calculated: radiosity, the power radiated across all wavelengths (according to the Stefan-Boltzmann law) and irradiation. For this study, the wavelength dependence of radiative properties is assumed as constant. Below the equations are presented respectively (c.f. Equation 4).

$$J = \rho_d G + \varepsilon e_b(T)$$
$$e_b(T) = n^2\sigma T^4 \qquad (4)$$
$$G = G_m + G_{amb} + G_{ext}$$
$$G_{amb} = F_{amb}\varepsilon_{amb}e_b(T_{amb})$$

Initial conditions

The mesh used is physics-controlled, normal or coarse element sizes can be used (a sensibility study was done). Explicit Selections were used in the Definitions menu to better identify the different parts of the tent (c.f. Figure 6).

Six different materials are used to define the whole model, four describing the tent's parts, one to represent the air and the last one to model the floor. The table below shows the materials' properties needed per physics (c.f. Table 1).

The initial values considered for the Flow physics were:
$u = [0\ 0\ 0]\ m/s$
$p = 0\ Pa$

Likewise, for the Heat Transfer in Fluids physics:
$T = 300.15\ K$

And finally, for the Surface-to-Surface Radiation physics:
Blackbody/Graybody condition was considered.

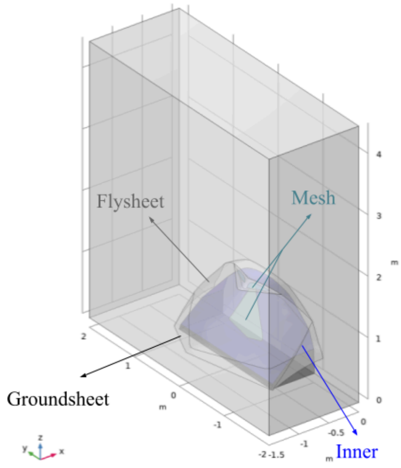

Figure 6. 3D model of the tent 2 SECONDS EASY -2 places- Fresh & Black.

Table 1*: Materials' properties needed per physics.*

Flow	Heat transfer in fluids	Surface-to-Surface Radiation
Density (kg/m³)	Heat capacity (J/kg·K)	Emissivity
Dynamic viscosity (Pa·s)	Thermal conductivity (W/m·K)	Transmissivity
		Reflectivity

For the non-specified variables above, default values proposed by COMSOL were taken into account.

Boundary conditions
To reduce calculation time, only the measurement zone will be simulated and not the whole thermal chamber. Meaning a space of 1.5 m x 4 m x 4.5 m. The ceiling and the walls are not physical walls (which are further away) or the real ceiling (which is higher than the spots' ramp). Additionally, a symmetry is considered in the longitudinal cross section to reduce the calculation time.

For each physics, specific boundary conditions were considered. Beginning with the Flow (c.f. Figure 7), where the whole tent structure was considered as an interior wall meaning that both sides of the textiles are interior boundaries. This feature allows discontinuities (velocity, pressure, and turbulence variables) across the boundary. On the other hand, the mesh part of the tent was defined as a Screen which corresponds to an interior model adapted to wire-gauzes, grilles, or perforated plates as thin permeable barriers [4].

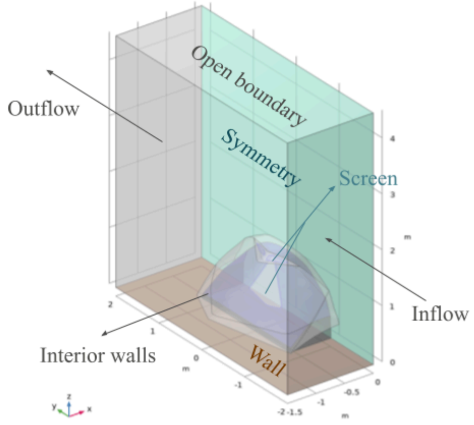

Figure 7. Flow's BC considered. Left wall (yz plane): Open boundary. Interior walls: groundsheet, inner & flysheet.

In addition, concerning the Heat Transfer in Fluids (c.f. Figure 8), the tent's parts are assumed to be thin layers, which means, these materials can be formed of one or more layers. Each layer can be constituted of multiple sublayers with specific thickness and thermal properties. This condition may also be used to enforce consistent initial conditions. Though, the mesh part of the tent was described as a thin film, which implies a fluid behavior (no resistance) but is a feature applicable on boundaries.

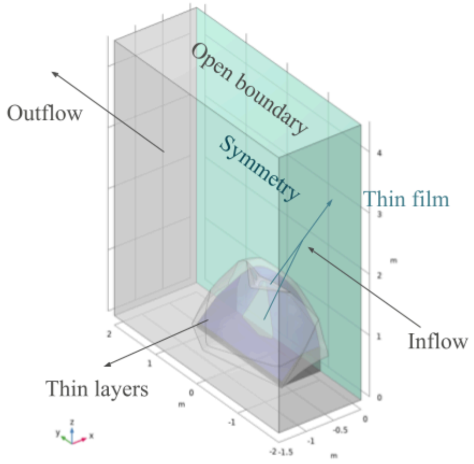

Figure 8. Heat Transfer in Fluids' BC considered. Left wall (yz plane): Open boundary. Floor: defined in Surface-to-Surface Radiation B.C. Thin layers: groundsheet, inner & flysheet.

Finally, for the Surface-to-Surface Radiation physics, only the floor and the tent are considered since this attribute is uniquely applicable for solids (c.f. Figure 9). Even if the tent's sides are assumed to be rigid walls, they are able to transfer heat because they are presumed to be semi-transparent surfaces (denoting that in addition to specular and diffuse reflection, specular transmission can also be considered on the surface) [5].

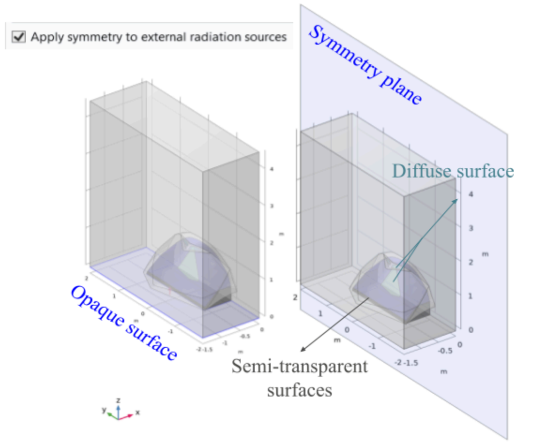

Figure 9. Surface-to-Surface Radiation's BC considered. Semi-transparent surfaces: inner & flysheet. Opaque (direction both sides): groundsheet walls.

Also, a diffuse surface is declared for the mesh part of the tent (c.f. Figure 10), which reflects radiative intensity uniformly in all directions. It is assumed that no radiation is transmitted through the surface [5]. Besides, an opaque surface was assigned to the floor and the groundsheet, meaning no radiation is transmitted through the surface.

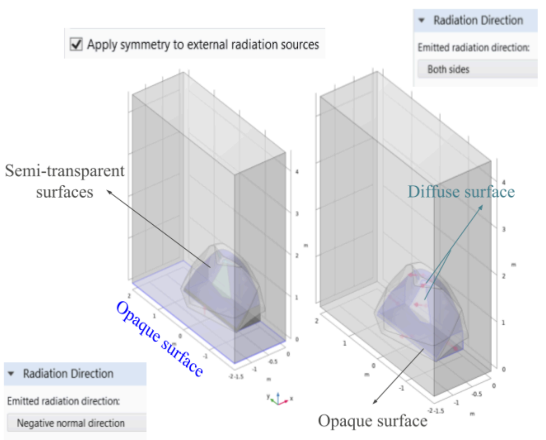

Figure 10. Surface-to-Surface Radiation's BC considered. Diffuse surface: mesh area of the tent. Opaque (direction negative normal): floor.

The approximations mentioned in this subsection are known and quantified as much as possible, in order to be aware of the final results' incertitudes.

Simulation app

No simulation app is finished or runnable at this stage of the project. Nevertheless, the final aim of this case study is to provide to the design engineers a simulation app as a predictive tool. This simulation application will allow Decathlon to rapidly test different materials and to optimize the design (geometry, aeration, etc.) considering thermal efficiency and eco-design constraints.

Definitely, the COMSOL Application Builder will accelerate the development of this simulation app and is the preferred identified tool for the achievement of the project.

Experimental Results Vs Simulation Results

For the first evaluation of the model, one tent was simulated: 2s EASY -2p- F&B. The model is built using a wind speed of 2 m/s, an ambient temperature of 27 °C and an external radiation source of 24 x 1400 W (taking into account the symmetry this will represent 48 spots which correspond to the number of working light bulbs at the lab). This value was estimated iteratively using an auxiliary sweep to get a surface irradiation of 750 ± 50 W/m² on the floor. Confronted experimental/numerical values are presented below (c.f. Table 2):

***Table 2**: Experimental/numerical results' confrontation.*

Tent model	Exp. measures	Numerical values	Difference
2s EASY -2p- F&B	31.5 °C	34.6 °C	1.4 %
	513 W/m²	522.4 W/m²	1.8 %

As illustrated (c.f. Figure 11), the air flows through the mesh sections of the tent, helping the decrease of internal temperature. Moreover, the surface irradiation is less important at the interior of the tent (c.f. Figure 12), which proves its capacity of blocking solar radiation. Both contributions provide a better thermal comfort to the user.

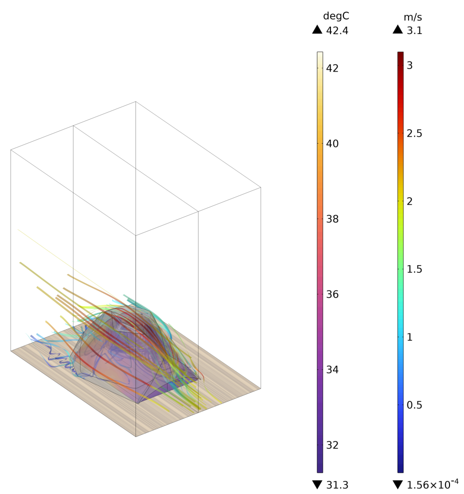

Figure 11. Nonisothermal flow turbulent results. Legend at the left side: temperature at the internal volume of the

tent in °C. Legend at the right side: flow velocity field streamline in m/s.

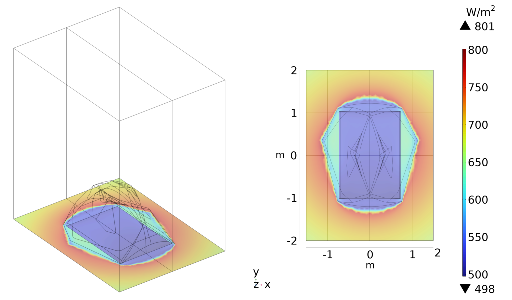

Figure 12. Surface irradiation (navy blue represents the best protection of the scale considered). Left: isometric view. Right: top view.

Conclusions

The numerical test reproduces the existing physical thermal test for the 2s EASY -2p- F&B tent, coherent results are obtained. Thus, the model is validated since a global difference of only 2 % is demonstrated when comparing experimental vs numerical results.

The main next step for the current numerical model is to test it considering the same tent structure but with classic textiles. This will allow us to quantify numerically, the advantage of using a F&B tent. Subsequently, bigger tents with different geometries should be analyzed to validate the reliability and robustness of the numerical model. Afterwards, a model for trekking tents will be developed, more critical conditions like condensation, will be considered. Heat and humidity data simulating the human interaction with the tent will also be taken into account.

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