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COMPUTATIONAL ANALYSIS OF CAKE FORMATION IN BAG FILTERS

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Abstract. *The growing concern with Environmental pollution, above all, the presence of particulate matter in the air made the industry look for ways to reduce or eliminate the release of these pollutants into the atmosphere. Bag filters are devices widely used in gas filtration and the formation of filtration cake is the objective of several studies. The present work proposes the use of a sub-routine (UDF), based on models in the literature to predict the cake formation in bag filters. The proposed model allowed the evaluation of the formation of the cake on the surface of the filter medium, allowing the evaluation of its structure and the pressure drop due to the presence of this phenomenon. The results showed that the proposed model is able to predict the formation of the filter cake and the increase in the accumulated mass caused an increase in the pressure drop.*

Keywords: *bag filter, cake resistance, Computational Fluid Dynamics.*

1. INTRODUCTION

Since the industrial revolution, in the 18th and 19th centuries, the growth of industry and cities has been affecting the air quality due to the pollution released into the atmosphere. Among the main air pollutants are particulate matter and gases from combustion processes, especially from fossil fuels (Augusto, 2014).

In view of the concern with the quality of atmospheric air, the industry, in general, was forced to implement resources to control the emission of pollutants in the atmosphere. There are several ways to control air pollutants, with bag filters standing out among the most efficient particulate matter control devices (Rocha, 2010).

Bag filters are devices capable of removing particulate material from a gaseous stream through the filtration process that occurs in a porous membrane, usually constructed of organic or synthetic fibrous material capable of retaining the particulate material, allowing the air released into the atmosphere to be clean or within the concentration of particulate material specified by the environmental regulations of each region. The bags are made of a kind of fabric that involves a metallic structure, usually cylindrical, in which the air is forced to pass through, by a mechanical fan, leaving the particles attached to the fibers of the material or to the surface, giving rise to the filtration cake (Rocha, 2010).

During the filtration process, the particles initially penetrate into the fabric fibrous and stick to it. This process is known as internal filtration and is only relevant at the beginning of a filtration cycle. Over the time, the interior of the fabric becomes saturated and the deposition of particles starts to happen on its surface, giving rise to the formation of the filter cake that increases in thickness as the mass of particulate material increases.

Although experimental studies have evaluated the formation of filter cakes, the costs related to the assembly of these devices are high and the accuracy of the evaluations can be questioned. Seeking to facilitate analysis and contribute with relevant information for equipment designers, the CFD (Computational Fluid Dynamics) technique is widely used because it allows the reproduction of real models without the need to build an experimental apparatus.

Authors such as Bernabé (2016) and Lima (2019) evaluated the fluid dynamics in bag filters using the CFD technique with single-phase flow to propose improvements in the construction of the equipment. Although the technique is easy to apply for purely evaluation of fluid dynamics, the process of formation of the filter cake is complex and needs to be developed. Therefore, the present study aims to propose a User-defined function (UDF) for analysis of the formation of the filter cake in fabric filters.

2. METHODOLOGY

2.1 Porous media model

The present work aim to develop a methodology to represent the formation of the filter cake in filtration operations. The experiments carried out by Rocha (2010) were used as a database to validate the proposed model.

In computational simulation, fabric filters are modeled as porous media of known permeability and porosity. The Ansys Fluent© porous media model adds a moment source term to the standard flow equations. The pressure drop is then modeled by combining Darcy's law with the addition of an inertial loss term, according to Eq. 1.

$$\Delta p = -\left(\frac{\mu}{\alpha} v + C_2 \frac{1}{2} \rho v^2\right) \Delta m \tag{1}$$

Where μ is the fluid viscosity, α is the permeability of the porous media, C_2 is the inertial loss coefficient, v is the normal velocity at the porous surface and Δm is the thickness of the media. In filtration operations, the filtration velocity is generally low, allowing the inertial loss term to be neglected from Eq. 1 without major damage to the accuracy of the results.

2.2 Discrete phase modeling

The dust particles were modeled as a dispersed solid phase represented by the Lagrangean method, using the discrete phase modeling of Ansys Fluent©. This model is recommended when the volume of the solid phase is less than the volume of the fluid phase to the point of allowing the particle-particle interaction to be neglected.

In this model, the trajectory of the particles is calculated individually during the calculation of the fluid phase.

The software calculates the path of the discrete phase by integrating the balance forces on the particle in a Lagrangian framework. This balance of forces is determined by Eq. 2.

$$m_p \frac{d\vec{u}_p}{dt} = m_p \frac{\vec{u} - \vec{u}_p}{\tau_r} + m_p \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F} \tag{2}$$

Where m_p is particle mass, $\vec{u}$ is the velocity of the fluid phase, $\vec{u}_p$ is the particle velocity, ρ is the fluid density, ρ_p is the particle density, $\vec{F}$ is an additional force, the $m_p \frac{\vec{u}-\vec{u}_p}{\tau_r}$ represents the drag force and τ_r is the particle relaxation time given by Eq. 3.

$$\tau_r = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_r Re} \tag{3}$$

Where d_p is the particle diameter, μ is the fluid viscosity and Re is the relative Reynolds number, given by Eq. 4

$$Re \equiv \frac{\rho d_p \left|\vec{u}_p - \vec{u}\right|}{\mu} \tag{4}$$

2.3 Geometry and mesh

The computational domain consists in a cylindrical filtration box, in which the filter element is inserted in the middle of the section as a porous domain with 2.5 mm thickness and 195 mm in diameter. Further details of the geometry used are shown in Fig. 1.

A mesh with prismatic elements was built to discretize the computational domain. A mesh test was carried out to verify the independence of the results in relation to the size of the mesh elements. The selected mesh has 1320844 elements and it is also shown in Fig. 1.

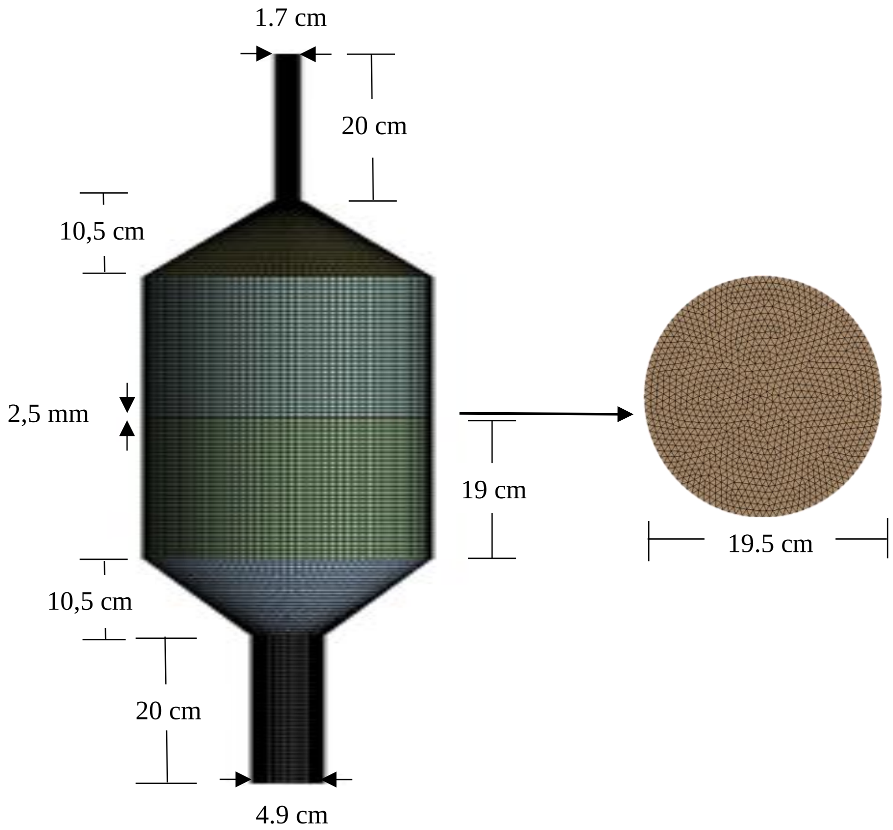

Figure 1. Computational mesh representing geometric dimensions of the filtration box.

2.4 Boundary conditions

The continuous phase was modeled with air flow by inserting a constant velocity profile at the entrance of the domain. The inlet velocities were 6.58 m/s and 19.74 m/s, calculated to provide filtration velocity of 5 and 15 cm/s, respectively. The air has a density of 1.225 kg/m³ and a viscosity of $1.7894e^{-5}$ Pa.s. The exit section is considered to be at atmospheric pressure and the walls present non-slip condition.

The discrete phase (solid material) was modeled using the discrete phase model (DPM) with a particulate mass flow of $3.1\ x\ 10^{-5} kg/s$ with a specific mass of $2.79\ g/cm^3$ and average particle diameter of $5.7\ \mu m$.

The filtration membrane was modeled using the porous media model described in section 2.1 with an isotropic permeability of $5.87e^{-10} m^2$ and porosity equal to 0.8. Additionally, a user-defined function (UDF) was written to provide the variation of the resistance of the porous medium with the deposition of the particles during the filtration operation.

When the filtration cake is formed, the flow resistance due to this phenomenon needs to be incorporated into the model. The total loss is then represented by the sum of the losses due to the filtering element and the losses related to the filter cake, which is dependent on the accumulated mass per unit area, according to Eq. 5 (Kavouras, 2003).

$$\Delta p = \frac{\mu}{A}\left(\alpha_m \frac{m}{A} + R_T\right)\frac{dV}{dt} \quad (5)$$

Where $\alpha_m \frac{m}{A}$ is the portion referring to the filter cake and R_T represents the resistance due to the fabric filter.

During the filtration cycle, the formation of the filter cake starts to have a strong influence on the head losses and needs to be included in the modeling. To predict this phenomenon, a sub-routine (UDF) was developed to calculate the thickness of the filtration cake as a function of the accumulated mass and allow the prediction of the pattern of cake formation and the increase in pressure drop.

In the developed UDF, the trajectory of the particles of the gas stream is monitored until it reaches the surface of the porous medium and, then, the particle mass is added to the cell and the properties of the filter medium are recalculated. A schematic representation of this process is shown in Fig. 2.

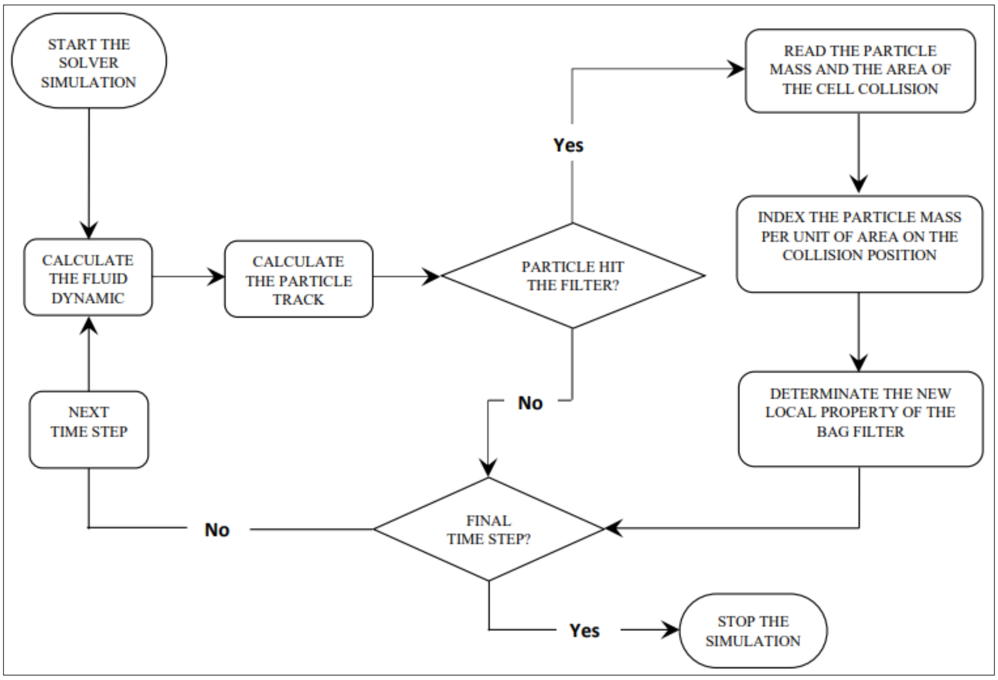

Figure 2. Schematic representation of the UDF solution process.

Regarding pressure interpolation, the scheme PRESTO! was applied. For the pressure-velocity coupling, the SIMPLE algorithm was used. For the other variables, the second order UPWIND interpolation scheme was used. The turbulence model adopted was the k-ε realizable.

3. RESULTS AND DISCUSSIONS

For filtration velocity of 5 cm/s, the transient simulations were performed up to 280 s, while for the speed of 15 cm/s the simulations performed up to 376 s. The results obtained by the simulations were compared with the experimental results obtained by Rocha (2010) for the first filtration cycle, which represents the not used fabric filter.

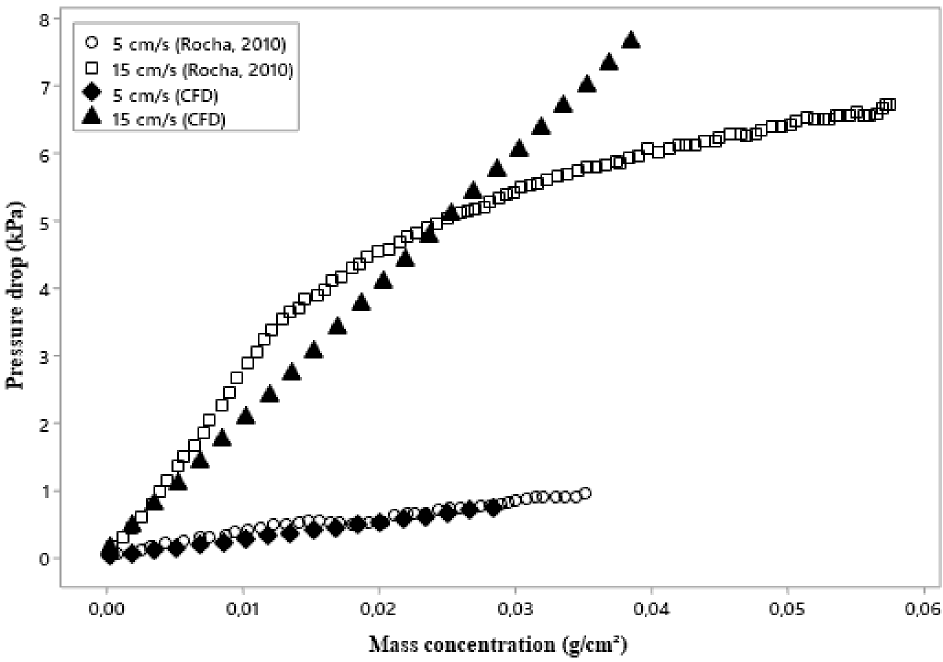

Figure 3. Pressure drop as function of mass concentration on filter surface.

The results obtained by Rocha (2010) showed that for the filtration speed of 5 cm/s, the pressure drop presents a practically linear behavior, that is, it varies linearly according to the amount of mass deposited on the filter surface. This behavior can be explained by the low filtration velocity that cause little penetration of the particles inside the filter medium, changing little the resistance of the medium to flow. Thus, the increase in pressure drop is now represented by the addition of the resistance term of the cake that forms on the fabric surface. As the model described by the UDF does not consider internal filtration, the results obtained through CFD simulation showed good agreement with experimental results of Rocha (2010).

Also in Fig. 3, for filtration velocity of 15 cm/s, the penetration of particles into the fabric starts to have a strong influence on the behavior of the pressure drop, especially at the beginning of the operation. In this step, the penetration of the particles into the fabric changes the properties of the filter medium, generating a more inclined curve at the beginning of the filtration. With the saturation of the filter medium, the deposition of particles starts to occur only on the surface of the fabric and the increase in pressure drop is dominated only by the formation of the cake. Therefore, for higher filtration velocities, the proposed model encounters difficulties in predicting the pressure drop. New adjustments and the inclusion of correlations that can predict the stage of internal filtration will be necessary to increase the range of operation of the proposed model and refine its precision.

The mass of particles adhered to the surface of the fabric filter was also analyzed. In Figure 4, it is possible to observe the gradual increase in the accumulated mass during the simulation, confirming the applicability of the model developed to predict the formation of the filter cake. It is also possible to observe that the pattern of particle deposition presents a similar behavior regardless of the filtration velocity. There is a preferential area for the deposition of particles in a medium region located between the axis and the walls of the filter box. This behavior is due to the velocity field upstream of the filter.

The resistance created by the filter caused the flow jet to spread radially in the filter section, as observed in Fig. 5 for the simulated results. Such behavior was also observed by Rocha (2010). Additionally, the spreading of the jet causes a change in the direction of the particulate material, causing the annular pattern of cake formation as seen in Fig.4.

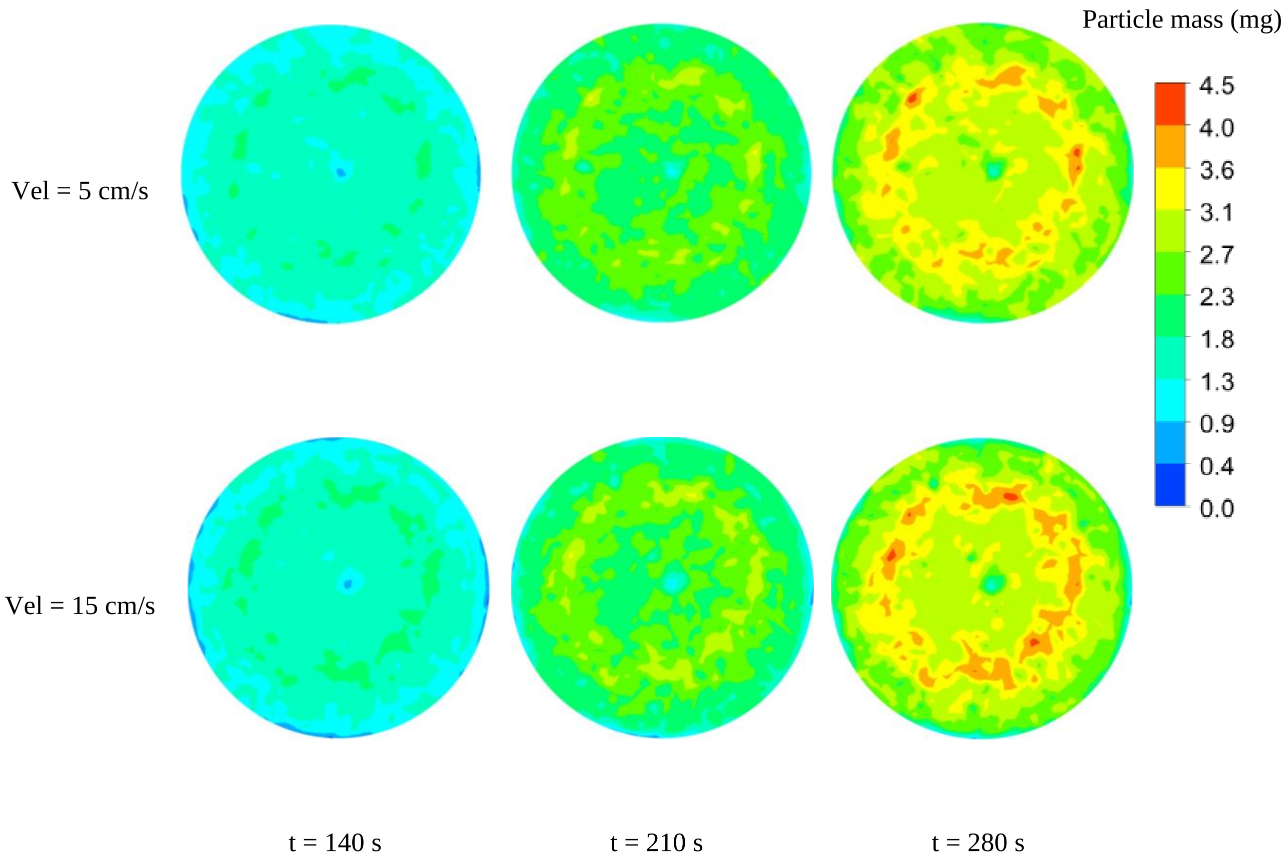

Figure 4. Mass of particles deposited on the filter during the simulation time.

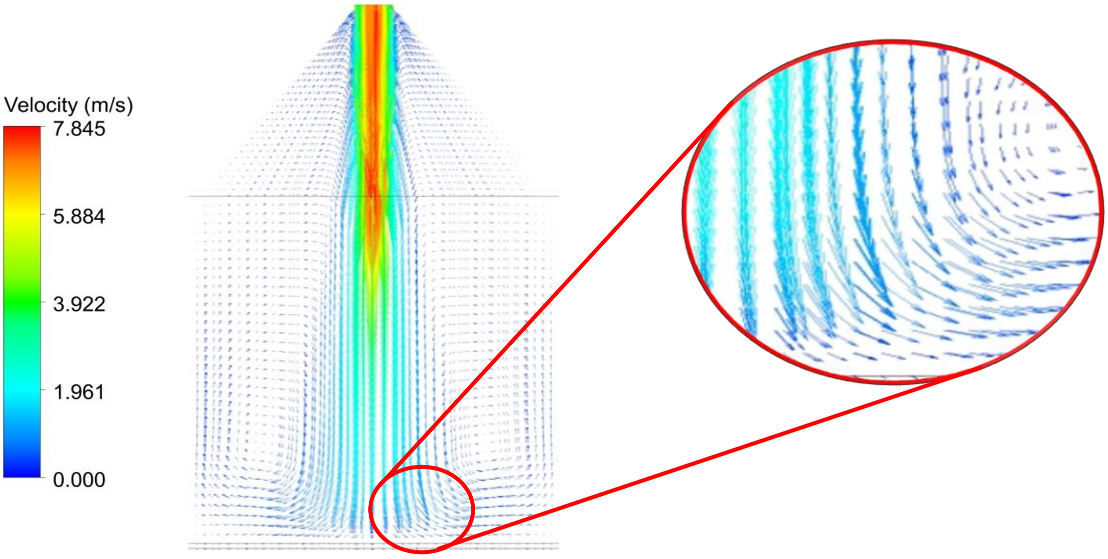

Figura 5. Velocity profile at initial time for filtration velocity of 5 cm/s.

4. CONCLUSIONS

The present work showed a method for predicting the formation of the cake in fabric filters using numerical simulation as an alternative to the experimental methods of evaluating the structure of the cake. The model allowed to evaluation of the formation pattern of the cake and its impact on the flow field and pressure drop in the equipment. Although more detailed studies are needed to refine the model, the results of the simulations, especially for low velocities, showed good agreement with the data available in work Rocha's (2010) and may serve as a basis for studies of formation of the cake in fabric filters, saving time and cost when compared to experimental methods. The results obtained also showed the need for adjustments in the model so that it can predict other filtration phenomena, such as internal filtration. These adjustments will be topics for future works.

5. ACKNOWLEDGMENT

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6. REFERÊNCIAS

Augusto, L. L. X. Aplicação da fluidodinâmica computacional (CFD) no estudo do escoamento de ar e deposição de partículas em vias aéreas pulmonares. 2014. 110 f. Dissertação (Mestrado) – Programa de Pós-graduação em Engenharia Química, Universidade Federal de São Carlos, São Carlos, 2014.

Bernabé, A. C. A. Avaliação do escoamento e proposição de melhorias em um filtro de mangas utilizando fluidodinâmica computacional (CFD). 2016. 76 f. Trabalho de conclusão de curso – Graduação em Engenharia Ambiental, Universidade Federal do Espírito Santo, Vitória, 2016.

Kavouras, A. and Krammer, G., 2003. “Deriving cake detachment versus cake area load in a jet pulsed filter by a mechanistic model”. Powder technology, Vol. 133. P 134-146.

Lima, W. F. Análise da distribuição de ar em um filtro de mangas utilizando dinâmica dos fluidos computacional. 2019. Dissertação (Mestrado) – Programa de Pós-graduação em Engenharia Mecânica, Universidade Federal de Minas Gerias, Belo Horizonte (2019).

Rocha, S. M. S. Estudo da influência da velocidade e dos ciclos de filtração da formação da torta na limpeza de gases em filtro de mangas. 2010. 168 f. Tese (Doutorado) – Programa de Pós-graduação em Engenharia Química, Universidade Federal de Uberlância, Uberlância, 2010.

7. RESPONSIBILITY NOTICE