NUMERICAL PREDICTIONS OF AIR TEMPERATURE AND VELOCITY DISTRIBUTION TO ASSIST IN THE DESIGN OF FREE VENTILATION PIGGERIES

R. R. Mossad

Faculty of Engineering and Surveying,
University of Southern Queensland,
Toowoomba, QLD 4350, Australia.

ABSTRACT

Pigs are subjected to intensive environmental control and management for higher productivity due to their sensitivity to climatic variation. The climate affects pigs' growth and impacts greatly on the profitability of this industry. The aim of the current work is to numerically model the air velocity and temperature in a free ventilation piggery for grower pigs (32-52 kg) and to investigate the effect of variation in the design on the environment inside the piggery and more specifically at the pigs' level. . These variations were reducing the height of the outer wall of the piggery to the same level as the pens and changing the type of fence used in the pens as well as adding louvers in the air opening, changing the shape of the roof and adding insulation to the roof. A steady two-dimensional numerical model based on the integral volume method including the effect of buoyancy, turbulence and heat generated by the pigs was solved using the computational fluid dynamics software Fluent. The results suggest that varying the type of fence from a solid internal fence to one made of separated bars (new fence) did not have much impact on the environment inside the piggery. When this change was combined with the other variation such as lowering the outer walls it made some improvements. Combining the new fence, lowering the outer walls and changing the shape of the roof resulted in the highest increase in the air speed of about 0.2-0.4 m/s at the pigs' level. These improvements would be only sufficient in milder climate. If these variations were combined with appropriate water sprayers it will help to meet the pigs' thermal comfort limit at that hot climate.

Keywords. Pig housing, computational Fluid Dynamics, natural ventilation.

INTRODUCTION

Pigs are reared under more intensive conditions than other farmed animals because of their unique nature. Their growth varies with their living environment and they are very responsive to climatic variation (Kilgour and Dalton, 1984, Turner et al., 1997, Fritschen et. al., 1974). Therefore, they are subjected to intensive environment control and management for higher productivity.

Piggeries are either forced ventilated or free ventilated. Forced ventilation is the preferred option for young pigs. This is to achieve better control of temperature, since their tolerance to variation of temperature is much less than older pigs. Free ventilated piggeries require positioning in particular directions to make use of the prevailing wind and the solar energy available to achieve the proper environment inside the shed at minimum cost. Free ventilated piggeries are cheaper to run; however the designer has much less control of the environment and so they suit older pigs.

Most previous research conducted to predict the thermal conditions inside a piggery, whether steady or transient, was based on the one-dimensional heat balance (Usry et. al., 1992, Albright, 1989 and Axaopoulos et al., 1994 and 1992). A one-dimensional analysis is only capable of predicting average temperatures. An average temperature may be within the comfort zone for the animals, but the maximum and minimum temperatures within the domain may not. A good design aims at achieving uniform temperature and wind speed at the animals' level so that the majority, if not all of the animals, are in their thermal comfort region.

The aim of the current work was to numerically predict detailed air velocity and temperature distributions inside a free ventilation piggery and at the pigs' level for a particular piggery as some variation in the design is made in order to examine which design best meets the thermal comfort of the pigs. A model that takes the effect of buoyancy, turbulence and heat generated by the pigs was developed using the software Fluent (Fluent Incorporated, 1997) to investigate the effectiveness of the different proposed designs. This numerical approach can be used as an aid to help identify problems in existing piggeries and offer suggestions for improvements in the design to achieve optimum environment inside the piggery faster and cheaper than conducting experiments in a prototype model.

MATHEMATICAL MODEL

Ideally, a three dimensional analysis would be needed if detailed velocity and temperature distribution within the domain of study needs to be known accurately. However, a two-dimensional model is sufficient if the piggery is designed to be narrow and long and air inlet and outlet is designed in such a way to maintain uniform airflow within the piggery, which is the case in many free ventilation piggeries in Australia.

In order to predict air velocity and temperature in a piggery, the continuity, momentum, and energy equations have to be solved simultaneously. These equations for incompressible, steady, two-dimensional and turbulent flow including the effect of buoyancy forces and heat generated by the pigs are given in equations (1-4) below.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=g\beta(T-T_\infty)-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{\dot{q}}{\rho c} \tag{4}$$

In these equations, u, v, p, and T are the average velocities in the x and y directions, the average pressure and temperature, respectively, while ρ, ν, β, α, g and $\dot{q}$ are density, kinematic viscosity, coefficient of thermal expansion, thermal diffusion coefficient, acceleration of gravity and rate of heat generated by the pigs/unit volume, respectively. Equation (1) is the continuity equation, which is the condition for the conservation of mass. Equations (2) and (3) are the conservation of momentum in the x and y directions, respectively. They are Newton's second law of motion in x and y direction, which equate the mass time acceleration to the sum of the gravitational force, pressure forces and viscous forces. Equation (4) is the conservation of energy, which include energy transfers due to convection, conduction and heat generation. The above governing equations are non-linear partial differential equations for which a closed form solution is not possible. Fluent software was chosen to solve these equations, due to its good capability, user-friendliness, availability and the author's familiarity with it. This software uses a control volume based finite difference method. The governing equations are discretised on a curvilinear grid to enable computations in a complex domain. Interpolation is accomplished via a first-order Power-Law scheme or optionally via a higher order upwind scheme. The equations are solved using a semi-implicit algorithm with an iterative line-by-line matrix solver and multigrid acceleration. A variety of turbulence models are available to choose form. In particular the k-ε turbulence model (Fluent Incorporated, 1997), which is commonly used in industrial problems due its robustness, economy and validity for fully turbulent flows, was chosen in this work.

To solve any flow problem using Fluent, one needs to divide the domain into small control volumes, which constitute the grid. The choice of the size of the control volume depends on the expected behaviour of the flow. Small control volumes were chosen wherever great variations of the variables are expected so that velocity, pressure and temperature of the flow in these regions can be accurately predicted. Larger control volumes were chosen outside these regions to reduce the memory needed, which reduces the time needed for the analysis.

Appropriate boundary conditions need to be applied, such as the air inlet velocity and temperature, type of building materials used, thickness and external conditions such as windy or calm air, which will impact on how much heat will escape the building. External conditions can be implemented either by specifying a temperature, a heat flux or a convection type boundary condition. Details of the different boundary conditions used in this model are given below. An initial solution needs to be chosen and an iterative procedure is followed until the residuals of all parameters solved for meet a set convergence criterion. The residuals are estimated as the imbalance in satisfying all governing equations summed up over all the computation control volumes. These parameters are continuity, velocity components, energy and turbulence parameters k and ε. The software has post-processing capability to graphically present the results in many different ways.

DESCRIPTION OF THE FREE VENTILATION PIGGERY

Some of the important parameters that affect air temperature and air speed at the pigs' level in a free ventilated piggery are orientation of the building with respect to the prevailing wind in the area, wind temperature $T_{in,}$ and velocity V_{in}, shape and dimensions of the shed, size and position of air openings, building materials of the shed, and heat generated by the pigs $\dot{q}$, which is a function of many parameters, such as their age, their feed, their state such as standing, sleeping, etc.

The piggery modelled in this work has the dimensions 47.55 m x 22.4 m x 4.65 m, which is occupied with grower pigs (32-52 kg) at a density of around 0.4 m^2/pig (according to the recommendation of Taylor et al. (1994)). The building length is aligned to the north south direction. The floor and the sidewalls are made of concrete. The roof is made of carbon steel and split into three parts, a flat part in the middle and two sloped parts on the sides, at a lower level below the middle part, leaving an air opening between the higher and lower parts, as illustrated by the solid black lines in figure 1. The two sides of the building are mechanically controlled to open completely in summer for maximum ventilation and to be fully closed on cold winter days.

A two dimensional model was chosen with the dimensions 22.4 m x 6 m. The domain of the study was chosen to extend above the highest point in the building by 1.35 m to include the air flowing over the building. This choice of the domain of study was to avoid imposing unrealistic boundary conditions such as defining the amount of air coming out of the high air opening, since this amount is variable and depends on many factors, so it can be determined appropriately based on the air mass balance in each case.

Pigs are modelled as circles with diameter 0.24 m, they produce a constant amount of heat, which was chosen as 35 W/pig (following Jones and Friday, (1996)). The thermal boundary conditions on the external walls were taken to be convection to the ambient temperature, which was chosen to be at 34^{o}C. The heat transfer coefficient h_c was taken as 10 W/m^2 K on the side of the building where the wind was blowing and 5 W/m^2 K on the other side where air is considered to be calm. The roof temperature was taken as 47^{o}C due to solar radiation and floor temperature was taken as 33^{o}C. A free shear boundary condition is used at the upper boundary, which means that the effect of the building on the ambient air movements at that boundary has diminished. Wind speed was taken as 0.92 m/s to the southwest. The ambient temperature and wind speed was chosen based on actual measurement taken at the piggery under study on a particular day. The sides were assumed to be fully open to allow for maximum ventilation since the ambient temperature was high.

RESULTS OF FREE VENTILTION PIGGERY

The current design of the piggery was modelled first to facilitate comparison with the results obtained for any variation of the design. Four modifications in the piggery design were proposed. These involved changing the solid internal fences to ones made of separated bars called the new fence in this work instead of a solid fence, lowering the outer walls of the piggery to increase the air flow and get it closer to the pigs' level, adding some louvers in the air opening between the high flat roof part and the lower sloped parts of the roof, to guide the air entering the room and reduce short circuiting, and adding a solid U shape to the high flat roof. The solid U shape was chosen to direct the air down to reach closer to the pigs before it escapes from high roof outlet. Each of these variations were added to the original design and modelled by themselves and when combined with other variation, but the combination that gave obvious improvement were the ones given below. Results showed that changing the fence to the new fence alone did not show much difference in either temperature or velocities across the piggery, with respect to the original design. However when combined with lowering the outer wall it started to have an effect. Results show that, it enhanced the air capacity of removing heat by about 77.5 watts. The heat capacity q was estimated based on equation (5).

$$q = c_p \dot{m} (T_i - T_o) \tag{5}$$

where c_p is the specific heat for air, $\dot{m}$ is the mass flow of air entering the piggery, T_i is the air temperature at inlet and T_o is the average air temperature at exit.

The flow streamlines, defined as the lines that are tangential to the air velocity, for the original design, the case with the new fence and lower outer walls, the case for added louvers to the new fence and lower outer walls and a case for an added solid shape to the new fence and lower outer walls, are shown in Figures 1-4. These streamlines are drawn in the domain in such a way that constant air flow is maintained between each consecutive streamline. This means that close streamlines represent high velocities while far away streamlines means low velocities. From these figures one can find that lowering the outer wall and using the new fence brought the air flow closer to the pigs at higher speeds, as can be seen from Figures 2-4, the streamlines are lowered and became much closer to each other than in Figure 1. This enhanced the capability of the air to carry more of the metabolic heat produced by the pigs as well as any pollution which may be present. Higher air speeds also help the pigs to tolerate the high temperature.

Figures 5 & 6 give a comparison of velocity and temperature variations at the pigs' level across the piggery for all above four cases. The pigs' level was chosen to be at 0.5 m above the floor. Figure 5 shows that in all three combinations mentioned above the velocities were higher than the original design in the majority of the piggery. The case with the solid shape shows the highest increase in the speed, between 0.2 - 0.4 m/s. In regard to the temperature variation across the piggery, the temperatures were lower than the original design particularly in the first 4 m, where the maximum temperature difference was 5 ^{o}C. However, in the rest of the piggery it seems that the new designs have sometimes higher temperatures than the original design, which could be due to the ability of the air to carry more of the pigs' metabolism heat than the original design. This is because lowering the outer wall and using the new fence allowed the air to get closer to the pigs, as mentioned above.

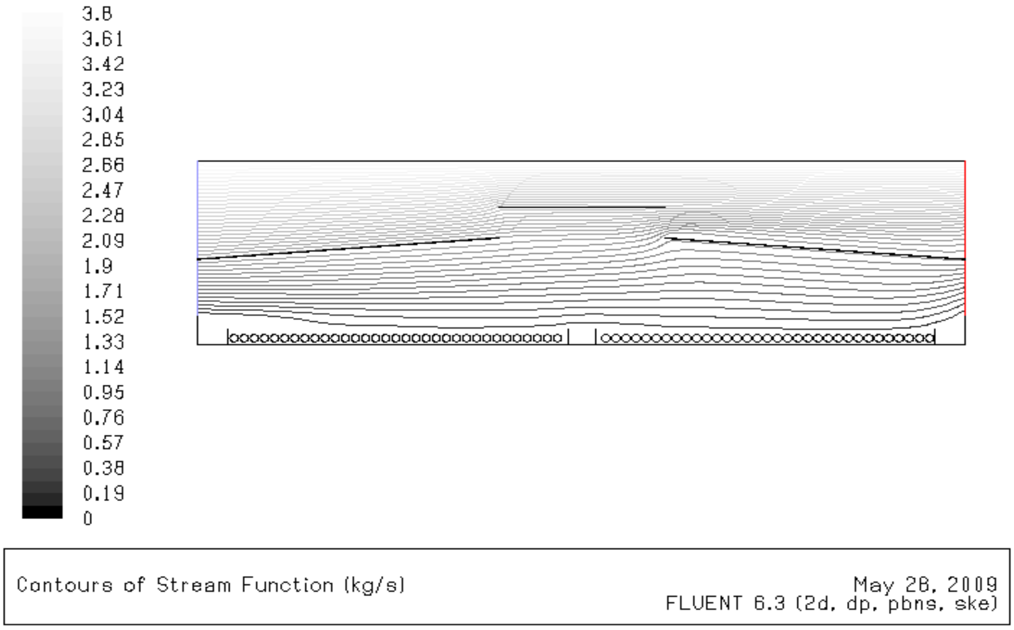

Figure 1. Streamlines for the original design

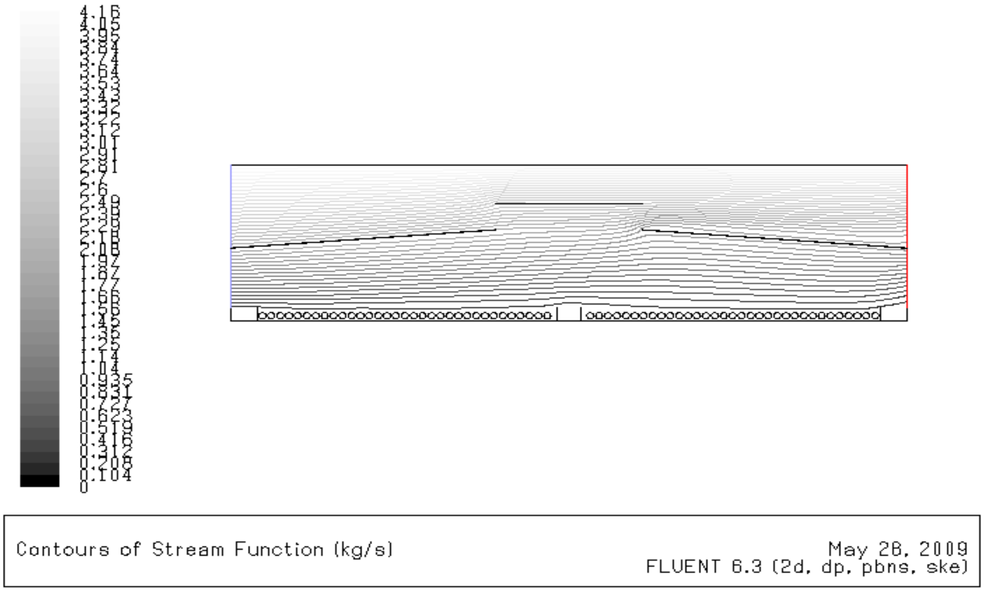

Figure 2. Streamlines for the lower outer walls and new fence

According to Gardner et. al. (1990), the thermal comfort zone for growers varies between 16^{o}C – 21^{o}C at air velocities of 0.15 m/s. Also, from one of the figures presented by Gardner et. al. (1990), which relates temperature to air speed, one can conclude that an increase of 0.1 m/s in the air speed increases the tolerance of the pigs by about 1^{o}C. This is also supported by Taylor et al. (1994), when they gave the higher limit of the thermal comfort for growers is 32 degrees with draughty air speed. This shows that none of the designs addressed in this study offer an environment that is in this thermal comfort zone, however the changes suggested here brought the air in the room somewhat closer to meeting the thermal comfort criteria. In order to meet the thermal comfort of the pigs at this hot ambient temperature, cooling with water sprayers should to be used in conjunction with the changes suggested. Water spray cooling is normally used in this climate; however it was not included in this modelling exercise.

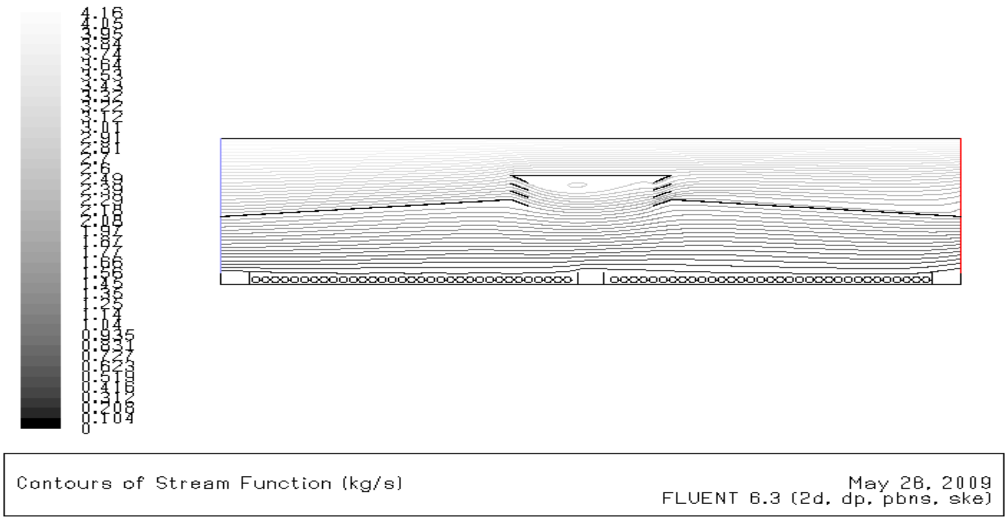

Figure 3. Streamlines for the case with louvers, new fence and lower outer walls

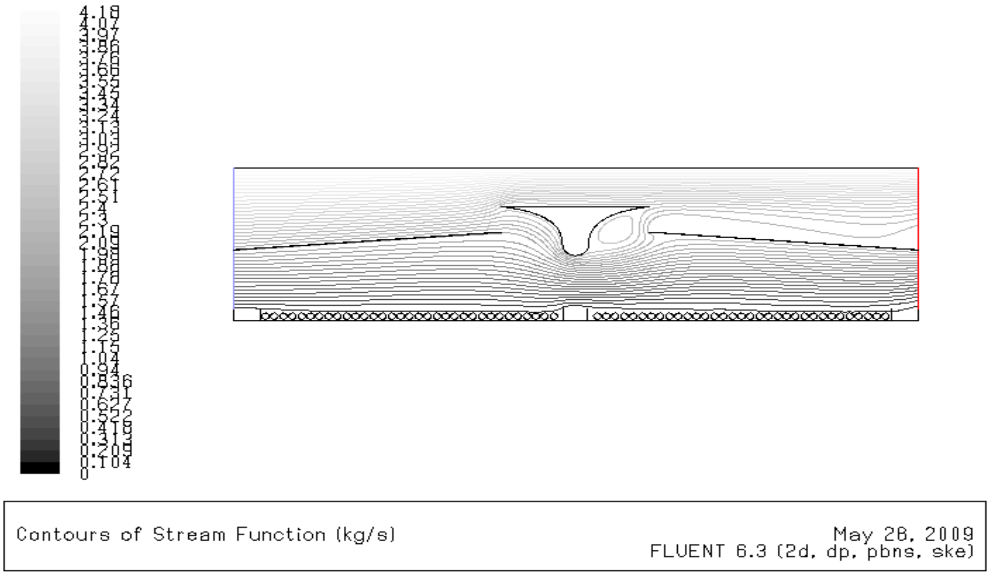

Figure 4. Streamlines for the case with solid shape, new fence and lower outer walls

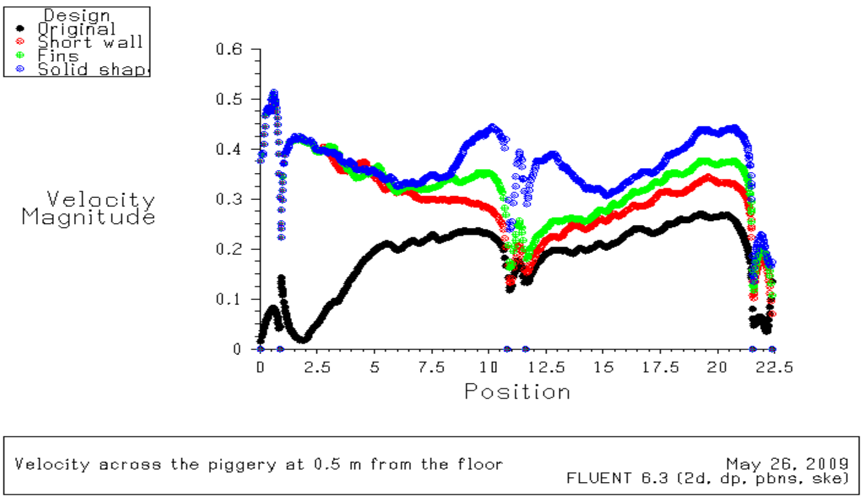

Figure 5. Comparison for the velocity distribution at the pigs' level for the five designs.

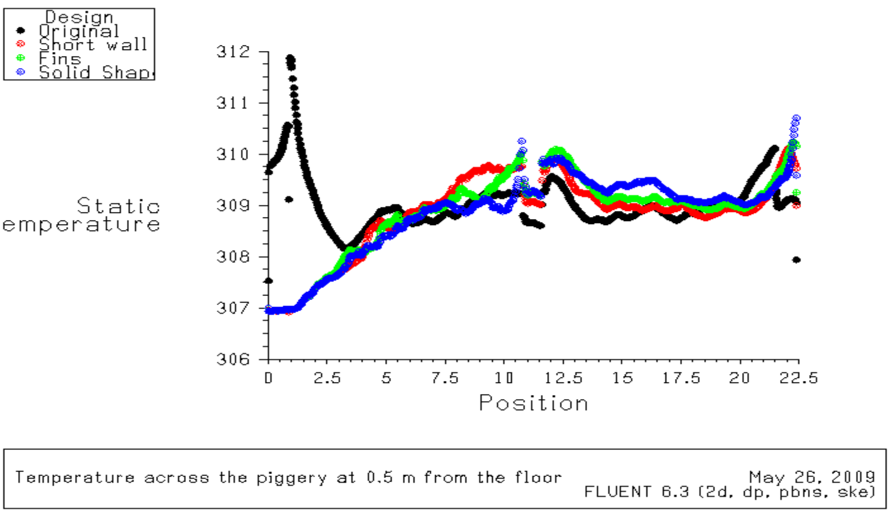

Figure 6. Comparison of the temperature distribution at the Pigs' level for the five designs.

CONCLUSIONS

Velocities and temperatures of air for a free ventilated piggery at the pigs' level were predicted for the original design as well as some variation in the design such as a new fence made of bars, lower outer walls, adding louvers at the air opening or adding a solid shape to the roof.

The results suggest that the design with lower outer walls combined with the new fence and adding a solid shape at the roof will result, if combined with appropriate water sprayers (however, this still need to be verified), in a better ventilated room that meets the pigs' thermal comfort level and is capable of renewing the air, getting rid of pigs' metabolic heat so that a healthy environment is maintained

The computational software Fluent proved to be helpful in analysing the airflow within the piggery and can be used as a valuable design tool. It helps in predicting the performance of a particular design and provides suggestions to improve existing designs in an economical way.

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