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CFD PREDICTION OF BUBBLES BEHAVIOUR IN 2-DIMENSIONAL GAS-SOLID FLUIDIZED BEDS

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ABSTRACT

In recent years the use of Computational Fluid Dynamics (CFD) is significantly increasing to simulate multi-phase flows. It is invariably emphasized that a necessary step towards the development of reliable fully predictive CFD models is an extensive experimental validation of the simulation results.

This work in particular focuses on the CFD simulation of a lab-scale 2D fluidized bed and the relevant experiments, in order to validate the prediction capability of the used codes and models. It must be emphasized that both experimental and computational quantitative data have been obtained by means of an original Digital Image Analysis Technique, that allows coherent comparison of computational and experimental data.

Due to the great importance of bubbles dynamic in affecting the fluidization quality, this work analyzes the capability of the CFD simulations in predicting the fluctuating behaviour of fluidized beds, by means of frequency analysis of bubbles related phenomena.

Keywords: Fluidization, Frequency analysis, CFD.

1. INTRODUCTION

Many of the characteristic features of gas-fluidized beds, like the excellent solid mixing, heat and mass transfer properties, can be related to the presence of bubbles and are dominated by their behaviour. A deeper knowledge of the fluidized bed hydrodynamics would provide the base for the development of a fully predictive model describing the gas solid flow in a fluidized bed.

The development of mathematical modelling of particulate solids behaviour together with the increased computing power enables researchers to simulate the fluidized powders dynamics and to link fundamental particle properties directly to the powder behaviour. In this regard, Computational Fluid Dynamics (CFD) provides a fundamental tool to support engineering design and research in multiphase systems. Many Authors recognise that computational modelling in multi-phase systems has the potential to increase process efficiency and reduce the number of scale-up steps in the design of reliable commercial plants. It is invariably emphasized that a necessary step towards the development of reliable fully predictive CFD models is an extensive experimental validation of the simulation results. The experimental validation will come to assess the suitability of the CFD model chosen to simulate the investigated regimes.

On the above basis, the present work focuses on the simulation of a 2-D fluidized bed operating under bubbling and slugging conditions carried out with the use of the commercial CFD code Ansys CFX-10.0. Computational results are firstly post-processed by a Digital Image Analysis Technique (DIAT, Busciglio et al. [2008]), to measure fundamental quantities such as bed height, bubble hold up, bubble diameter evolution and distribution, bubble velocity, and subsequently compared with experimental data (Busciglio et al. [2008]). Among all quantities available by DIAT, some of these are presented in terms of time series, i.e. bed height and global bubble hold up. In this work, a frequency domain analysis has been performed starting from data obtained by CFD simulation and relevant experiments, in order to fully validate the CFD reliability in predicting the evolution of time dependent quantity.

2. LITERATURE REVIEW

Dynamics of fluidized beds may be studied on the basis of time-averaged properties such as voidage and velocity profiles, bubble properties and/or on the basis of time dependent quantities (e.g. fluctuations in voidage and pressure), globally or locally in the bed. Both types of information are significant for the choice of the appropriate conditions for stable operation and control of the fluidized system. In the literature, there is a number of parameters whose evolution in time and space is chosen to characterize the dynamics of the fluidized bed. Frequently, pressure fluctuation measurements are chosen to investigate the hydrodynamic behaviour of fluidized beds.

Xu et al. [2004] studied time series signals by means of statistical analysis, frequency analysis (e.g. Fast Fourier Transform, FFT) and chaotic analysis, by which the behaviour of fluidized systems can be characterized and scaling-up relationships may be validated. Power spectrum densities of different flow regimes have different characteristics and thus they can be used to identify the flow regimes. The influence of sampling locations was also discussed.

Johnsson et al. [2000] compared time, frequency and state-space analyses of pressure measurements of fluidized beds. The results from the frequency domain (power spectra) and state-space analyses of the pressure fluctuations are generally in agreement and can be used complementary to each other. The power spectra can be divided into three regions, a region corresponding to the macro-structure (due to the bubble flow) and, at higher frequencies, two regions representing finer structures that are not predominantly governed by the macro structure of the flow. In all fluidization regimes, the measured pressure fluctuations exhibited an intermittent structure, which is not revealed by the power spectral analysis of the original signals.

Zhong et al. [2005] investigated pressure fluctuation frequency characteristics in a two-dimensional spouted bed. A multi-channel differential pressure sampling system was adopted to obtain pressure fluctuations and the modern ARM (Auto-Regressive Model) power spectrum was developed to estimate the pressure fluctuation major frequency. Effects of spouting gas velocity, fluidizing gas flow rate and static bed height on the pressure fluctuation major frequency were systematically examined. In addition, a digital camcorder was used to investigate through image analysis the gas–solid interactions in the bed. Preliminary investigation on the flow characteristics with the pressure fluctuation major frequencies indicates a promising way to study the complex gas–solid interactions and flow pattern transitions in spouted beds.

Lu and Li [1999] studied pressure fluctuations of bubbling fluidized beds to evaluate the fluidization quality. The information indicated by the pressure fluctuation signals can be used to analyse bubbling behaviours. The signals representing the characteristics of bubbling can be separated from original signals through discrete Wavelet analysis.

3. EXPERIMENTAL SET-UP

The fluid-bed reactor purposely designed and built for the present investigation is made of Perspex® with dimensions equal to 800 (height) x 180 (width) x 15 (depth) mm. The reactor is therefore almost two-dimensional, thus allowing visual observations of bubble dynamics within the bed. A plastic porous distributor, whose thickness is equal to 10 mm, is placed at the bottom of the particle bed. Below the distributor a wind box allows to equalize the gas flow. Glass ballotini in the size range 212-250 μm were used for the experimental runs with density equal to 2500 kg/m³. The particles were filled up to a bed height of 360mm, i.e. twice the bed width. The value of u_{mf} was experimentally determined and found equal to 5.24 cm/s. Also the value of gas voidage has been experimentally determined and found equal to 0.385. In these conditions the fluidized bed had a typical Geldart Group B system behaviour for both particulates. The investigated powder have been fluidized at different inlet gas velocities by ambient air, i.e 1.7, 3.4, 5.0 and 7.0 u_{mf} .

The bubble-related flow structures were visualized with the aid of a continuous back-lighting device and recorded by a commercial digital camcorder (Sony, model DCRTRV530E PAL), placed opposite to the bed at a distance of 270cm. The digital visual acquisition system allowed to collect images of the bed at a frequency of 25 Hz. Each experimental acquisition provides at least 500 frames, equal to 20 seconds of real time experiment. The image processing routine was developed on Matlab 7.3 (The MathWorks inc.), using the Image Processing Toolbox. The reader is referred to the paper by Busciglio et al. [2008], for full details on the experimental set-up adopted and measurement techniques.

4. COMPUTATIONAL MODELS AND METHODS

In this study the Eulerian-Eulerian Multi-phase Flow Model (MFM) coupled with the Granular Kinetic Theory (GKT) as presented in Gidaspow [1994] has been adopted to study the behaviour of gas-solid fluidized beds. This choice is a standard option of the CFD code Ansys CFX-10 purposely selected for this work. Continuity and momentum balance equations are thus solved for each phase using a classical Eulerian–Eulerian description. The standard GKT model is adopted for describing the behaviour of the granular phase and the Wen and Yu [1966] drag model is adopted to estimate the momentum exchange between phases.

As far as the numerical aspects are concerned, CFD simulations were performed in 2D mode choosing a computational grid consisting of 5mm square cells with 288(height) x 36(width) subdivision. The lateral walls were modelled using the standard no-slip boundary condition. The upper section of the simulated geometry, or freeboard, was considered to be occupied by gas only. A simple pressure boundary condition was imposed at the top of freeboard (i.e. fully developed flow condition). A Dirichlet boundary condition was employed at the bottom of the bed to specify a uniform vertical gas inlet velocity throughout the distributor. Symmetry planes were imposed on the front and rear faces of the simulated bed. The initial conditions specify only the distribution of solid volume fraction within the bed of solids which was set equal to 0.65. Typical running CPU times for CFX10 simulations were equal to about 100 hrs for 10 seconds of real time simulated with a fixed time step interval $\Delta t = 10^{-3}$s on a Dell

Dimension 8300 Personal Computer. The characteristics of the simulated case are identical to that experimentally investigated.

5. RESULTS AND DISCUSSION

The analysis of parameters such as time averaged bubble hold up and bed height, bubble size distribution, bubble local velocity has been reported in a previous paper (Busciglio et al. 2008).

It is worth noting that the time averaged quantification of such parameters, even if fundamental, is not sufficient for the correct assessment of the bubbling behaviour. In fact, the chaotic behaviour of bubbles causes the fluidized bed to never reach steady state conditions. On this basis, an helpful tool in data analysis is the power spectral analysis in the frequency domain of selected quantities. In particular the analysis was focused on the time dependent fluctuations of bed height (figure 1a shows the computational and experimental bed height for the case of $d_p = 212\text{-}250\ \mu m$, 3.4 u_{mf}) and bubble hold up (figure 1b shows the computational and experimental bubble hold-up for the case of dp = 212-250 μm, 3.4 u_{mf}).

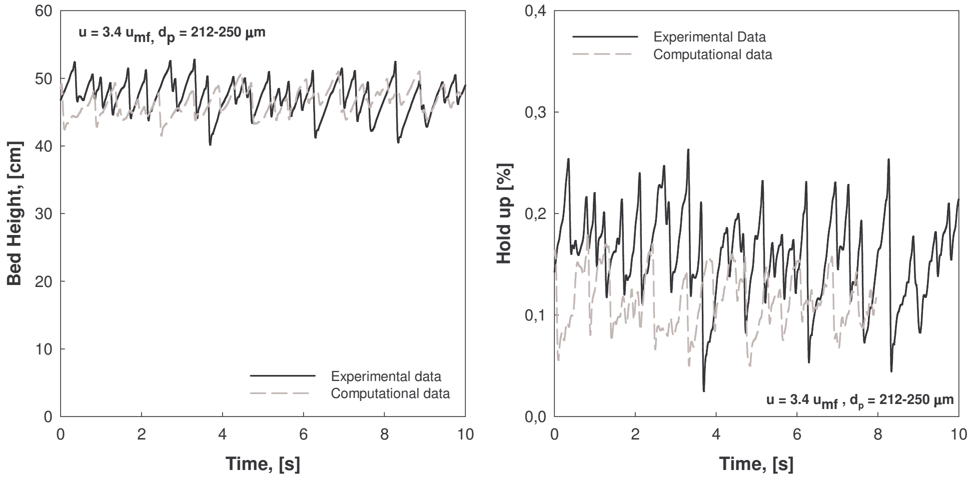

Figure 1. Comparison between experimental and computational data on instantaneous bed height (a), and bubble hold up (b) for the case at $3.4u_{mf}$-.

Moreover, local information on bubbling behaviour has been obtained through the analysis of the time dependent values of the local bubble hold up, computed in four Region Of Interest (ROI) in the bed. In particular, each ROI has the same width of the whole bed. The first ROI extends from the distributor to 0.25 H_0 (where H_0 is the settled bed height), the second extends from $0.25H_0$ to $0.50H_0$, the third extends from $0.50H_0$ to $0.75H_0$, and finally the fourth extends from $0.75H_0$ to $1.00H_0$.

In order to characterize the frequency domain behaviour of such time dependent quantities for all the investigated cases, the well known Fast Fourier Transform algorithm has been adopted (Duhamel and Vetterli [1990], Matlab 7.3 User Guide). This algorithm allows the detection of the frequency components of the fluctuating value of time dependent quantities. The comparison of computational and experimental data in the frequency domain allows the validation of the capability of the adopted CFD code in predicting the dynamic behaviour of bubbling fluidized beds.

In figure 2, the computational and experimental power spectral densities of the Fourier transform of the signals relative to bed height at different inlet gas velocities are presented. The frequency domain data obtained by FFT have been smoothed by means of a standard moving average algorithm. It is worth noting that both experimental and simulated spectral density curves clearly increase their average values when increasing the inlet gas velocity, as physically expected, due to the increasing intensity of bubble eruption. However, the simulated power spectra slightly underestimate the experimentally measured values of the power density. For all investigated cases it is possible to observe a characteristic power law decay trend (i.e. a linear decay in logarithmic charts) for both simulated and experimental spectra, especially in the frequency range of 2-10 Hz. As reported in the following, this kind of decay has been used to characterize the bubbling behaviour by means of the slopes and the intercepts of the fitting straight lines. It is expected that fully developed slug flows will ideally give rise to a single frequency peak, with pronounced decay rates. Conversely, bubbling regime is expected to give rise to less pronounced power decay rates with frequency. The CFD predictions of the power decay slopes are well satisfactory, being able to reproduce the bed surface dynamic in terms of decay rate.

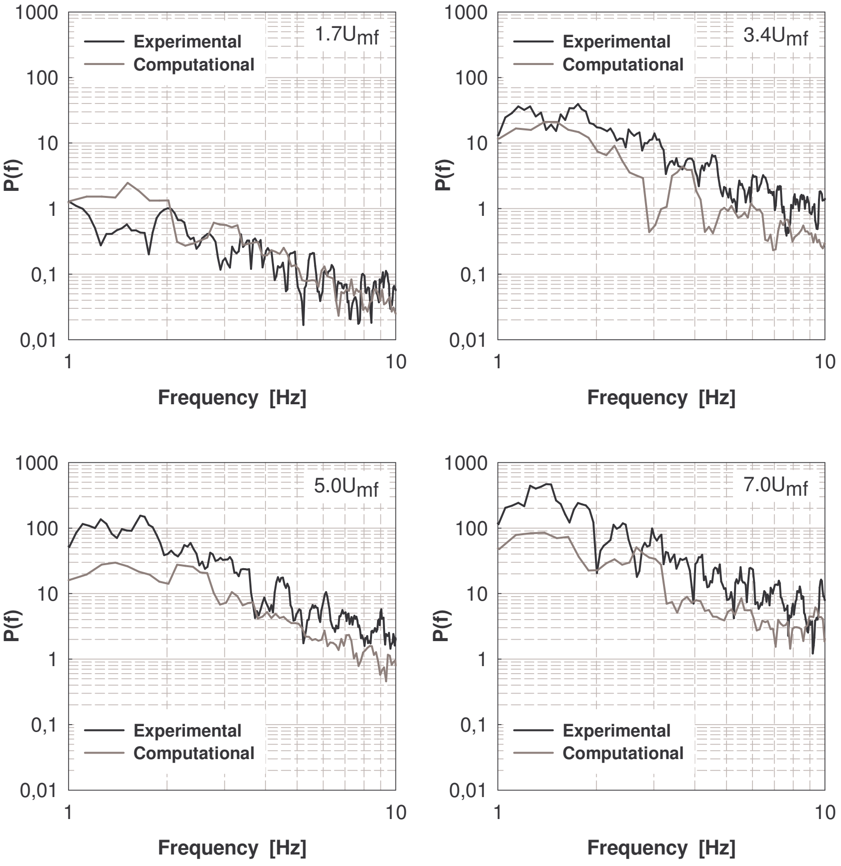

Figure 2. Comparison between experimental and computational power spectra of bed height at different inlet gas velocities.

In figure 3 the computational and experimental power spectra of the Fourier transform of the global bubble hold up is presented. Considerations quite similar to those made in the discussion of the bed height power spectra hold true to explain the physical role of such spectra power decay. It is worth noting that the bubble hold up follows a similar trend with respect to that of bed height.

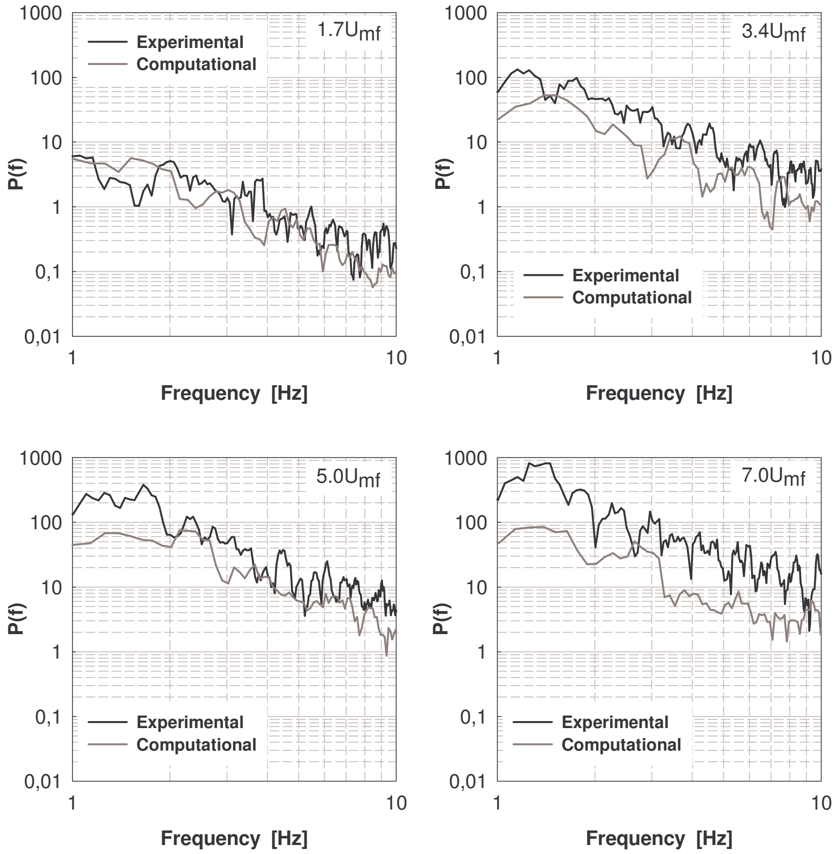

Figure 3. Comparison between experimental and computational power spectra of bubble hold up at different inlet gas velocities.

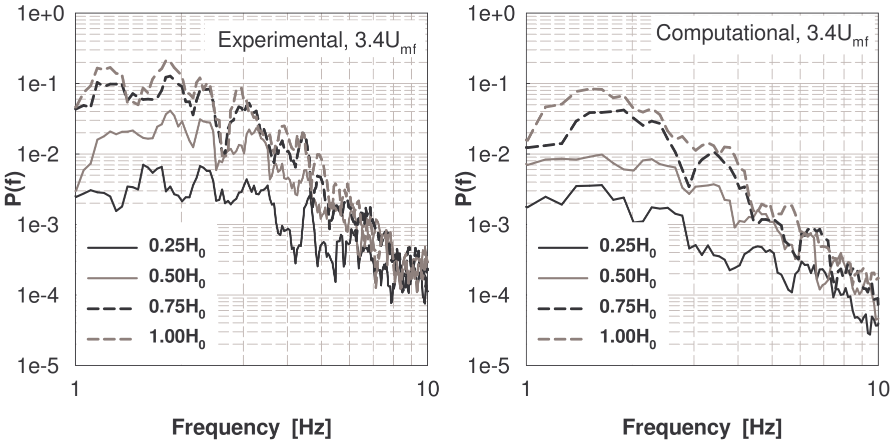

Figure 4. Comparison between experimental and computational power spectra of local hold up time series for the case at $3.4u_{mf}$-, at different elevations above the distributor.

The analysis of the experimental and computational power spectra of the local hold up at the four selected elevations, reported in figure 4 for the case at 3.4 u_{mf}, is useful to characterize the bubbling behaviour evolution with increasing distance above the distributor. An increase of the slugging behaviour when the distance above the distributor increases appears evident.

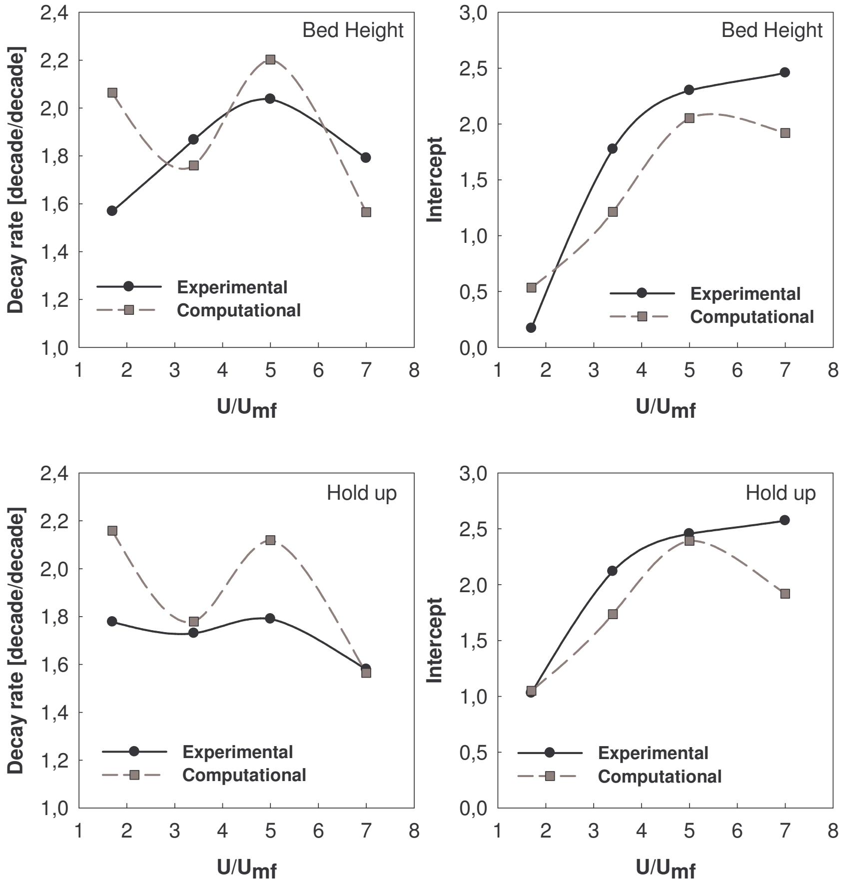

Figure 5. Comparison between experimental and computational power spectra fitting curves parameters for bed height and bubble hold up, at different inlet gas velocities.

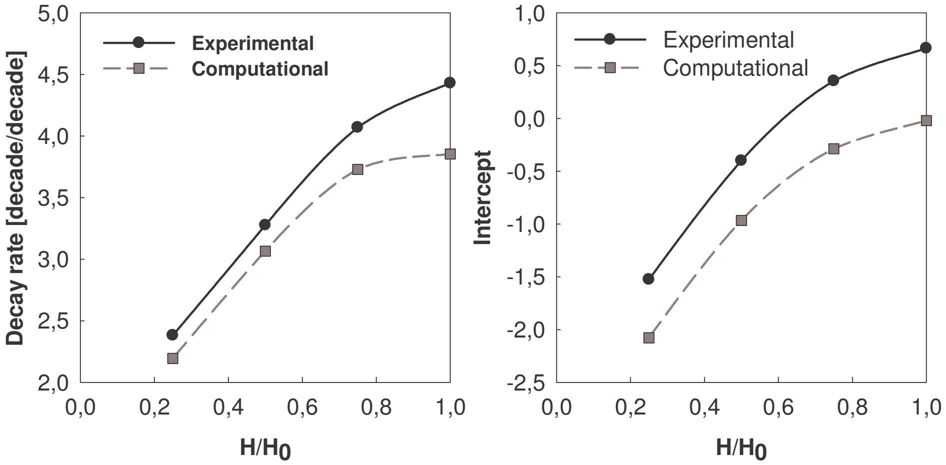

Figure 6. Measured values of experimental and computational decay rates for power spectra fitting curves parameters for local hold up at different elevations above the distributor, for the case at 3.4 u_{mf}.

In figure 5, the computed decay rates and intercepts of the fitting lines are reported. The analysis of the predicted decay rates highlights an articulate trend, with predictions giving rise to numerical values in acceptable agreement (within an order of magnitude) with experimental data. As far as the CFD predictions of intercept values are concerned, a substantial agreement with experimental data appears, although a slight underestimation is present. The power spectra fitting parameters of local hold up at different elevations above the distributor are reported in figure 6. Both the experimental and the computational decay rates and intercept values show an increase with elevation above the distributor. This is due to bubble coalescence phenomena that lead to the formation of bubbles having a more pronounced slugging behaviour at higher elevation ROI. It is worth noting on overall the good agreement between experimental and computational data of figure 6.

6. CONCLUSIONS

The present work focused on the simulation and characterization of 2D bubbling fluidized bed. The validation of simulation have been performed by the comparison of power spectral densities in the frequency domain of selected time dependent quantities, such as bed height, global bubble hold up and phase indicator. Pressure signals have been substituted by Digital Image Analysis based data, in order to decrease the influence of the probes on the systems. The simulations show a general agreement in the prediction of the presented power spectra, thus confirming the potential of CFD as a design tool for process engineering.

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