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# FLOW PATTERN AND PRESSURE DROP DURING AIR-WATER FLOW IN HORIZONTAL CHANNELS WITH FORCED VIBRATION

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**Abstract.** *This study presents an analysis of flow patterns during air-water flow in horizontal tubes with internal diameters of 6, 10, and 20 mm subjected to forced vibrations with the product of vibration amplitude and frequency ranging between 0.00 and 0.12 m·rad/s. The condenser and evaporating units of compact air-conditioning systems count with fans and compressors which transmit vibrations to the heat exchangers. Nonetheless, most of the studies available in the open literature for flow patterns, pressure drop, and heat transfer coefficient during boiling and condensation inside horizontal channels are performed for static conditions, with care taken to avoid movement of the test section. Therefore, most of the predictive methods are developed based on experimental databases obtained with static systems, while the operating device might be subject to mechanical vibrations. Hence, this study aims to present a flow pattern predictive method for gas-liquid flow in horizontal channels subjected to forced vertical vibrations based on a modification of the Taitel and Dukler method. The results with vibrations are compared with results without vibrations aiming to infer the effect of distinct operating parameters on the flow pattern. It is concluded that the transitions between smooth and wavy stratified, and between intermittent and dispersed flow patterns are more affected by the vibrations in comparison to other transitions.*

**Keywords:** *flow patterns, forced vibration, multiphase flow*

## 1. INTRODUCTION

Several methods for heat transfer enhancement have been proposed and evaluated aiming to obtain more compact and efficient equipment, even for conditions of convection for single-phase flow as well as for phase change processes. In this context, the research group of Bergles presented several literature reviews about methods for heat transfer enhancement (Bergles, 1997a, 1997b, 1999, 2002, 2011, Jensen e Bergles, 1997, Bergles et al., 2003, Bergles e Manglik, 2013), as well as Webb (1981, 2004). In general, these studies classify the enhancement methods as:

- Passive methods: comprise heat transfer enhancement methods that operate with no addition of external power to the channel and/or fluid. In general, these techniques are based on geometric or surface modifications. The modifications can be focused on the increment of effective heat transfer area and/or modification of the velocity field. The use of microfins, inserts (twisted tapes, coiled wires, etc.), surface roughness or wettability modification, corrugations, dispersion of nanoparticles, the addition of surfactant, etc.
- Active methods: comprise heat transfer enhancement methods based on the addition of external energy to the channel and/or fluid. In general, these methods consist in mixing the fluid to disturb the velocity profile, and to increase the heat transfer coefficient. Based on the literature review, it can be mentioned direct fluid mixing, channel vibration, electrostatic fields, suction and injection of fluid, and jet impingement.
- Compound techniques: heat transfer enhancement methods that combine two or more techniques, which can be all passive, active, or a combination of both types. It can be mentioned, for example, using twisted tape inserts in tubes with the porous surface (Bergles, 1999).

The number of studies and publications focused on the evaluation of passive enhancement methods is relatively high, as can be seen, based on the literature review listed previously, as well as in more recent studies presented by Kanizawa and Ribatski (2012), Mogaji et al. (2013), Kanizawa et al. (2014) and Piriyaungrod et al. (2015) for twisted tape insert, and Diani et al. (2014, 2018) and Kandlikar and Raykoff (2017) for two-phase flow in microfinned tubes. In general,

these studies are focused on the evaluation of thermo-hydraulic parameters, such as heat transfer coefficient, pressure drop, and flow pattern, followed by a comparison with the results for plain tubes with no enhancement. It can be concluded based on these studies that the heat transfer coefficient augmentation is accompanied by a pressure drop penalty, with a consequent increment of required pump power, which impacts the overall system efficiency negatively.

Conversely, the number of publications focused on active methods for heat transfer enhancement is limited in comparison with those of passive methods. Among the methods most widely used or investigated recently, it can be mentioned direct mechanical mixing of the fluid, use of agitators, and imposition of vibrations to the heat transfer wall. Nonetheless, most of the refrigeration systems count with compressors and/or fans and pumps, that inherently have moving parts, and eventually transmit vibrations to the heat exchangers. Therefore, the vibration of the channel wall might be intrinsic to most of the condensing and evaporating units of air conditioning systems. Despite this aspect, the vast majority of the experimental studies available in the open literature are performed for static channels.

In the case of flow condensation, it can be speculated that the vibrations might lead to liquid film breakup or thinning, which would result in an improvement of the heat transfer coefficient. Conversely, in the case of flow boiling, it can be speculated that the vibration would induce an earlier dryout of the channel wall, resulting in a reduction of the heat transfer coefficient.

Based on these aspects, this study aims at presenting an experimental investigation of flow patterns and pressure drop during air-water flow in horizontal channels subjected to forced vibrations, comprising channels in the micro, meso, and macroscale aiming to infer the dominant forces.

## 2. OBJECTIVES

The main objective of the proposed project is to predict flow patterns during air-water flow in horizontal channels subjected to forced vibrations. The following specific objectives can be listed:

- Modification of Taitel and Dukler (1976) predictive method to predict flow patterns during gas-liquid horizontal flow with forced vibrations.
- Compare the main trends and evaluate the main effects of the forced vibrations on the flow pattern transition.
- Describe the experimental facility in construction to validate the proposed method.

## 3. PROPOSED METHOD

Constantino (2021) performed a theoretical analysis focused on the influence of forced vibrations on the flow patterns during horizontal flow. In this study, the flow pattern predictive method proposed by Taitel and Dukler (1976) was modified by the inclusion of the vibrational Froude number, modified based on the proposal by Gaponenko *et al.* (2015), and given as follows:

$$Fr_{vi}^* = \frac{A\omega}{\sqrt{gd(1-\alpha)}} \quad (1)$$

where  $A$  is the vibration amplitude in m,  $\omega$  the vibration frequency,  $g$  is the gravitational acceleration,  $d$  is the channel diameter, and  $\alpha$  is the void fraction. The transitions are presented below.

### 3.1 Transition between smooth and wavy stratified

Based on the approach proposed by Gaponenko *et al.* (2015) for wave formation in a stagnant liquid film subjected to forced vibration, combined with the predictive method adopted by Taitel and Dukler (1976), which in turn is based on the method of Stewart (1967), the transition between smooth and wavy stratified flows can be given as follows:

$$Fr_v^* Re_l^{1/2} > (2 - Fr_{vi}^*) \frac{\alpha(1-\alpha)^{1/2}}{0,548} \quad (2)$$

where the Reynolds number for the liquid phase is given as function of the superficial velocity  $j_l$  as follows:

$$Re_l = \frac{\rho_l j_l d}{\mu_l} \quad (3)$$

and the vapor Froude number is given as function of the vapor superficial velocity  $j_v$ , as follows:

$$Fr_v^* = j_v \sqrt{\frac{\rho_v}{gd(\rho_l - \rho_v)}} \quad (4)$$

The void fraction  $\alpha$  in Eq. (2) is obtained based on the momentum balance of both phases, in a similar way to the proposal of Taitel and Dukler (1976) and rearranged based on the void fraction by Kanizawa and Ribatski (2021). In the case of null vibration, the transition criterion corresponds to the original proposal of Taitel and Dukler (1976).

### 3.2 Transition between stratified wavy and intermittent-annular

Gaponenko *et al.* (2015) evaluated the relationship between the Kelvin-Helmholtz instability criteria for the wave growth in conditions with forced vibration and concluded that the wave amplitude increases with  $Fr_{vi}^*$ . Based on this analysis, and combining it with the original proposal of Taitel and Dukler (1976), which is based on the balance of gravitational and pressure forces on a wave, the following transition is obtained:

$$Fr_v^* > \sqrt{\left[1 - \left(\frac{Fr_{vi}^*}{5}\right)^2\right] \frac{\alpha^3 \pi}{2 \sin \gamma}} \quad (5)$$

and  $\gamma$  is the stratification angle (0 rad for  $\alpha = 1$  and  $\pi$  rad for  $\alpha = 0$ ).

### 3.3 Dispersed bubble flow pattern

According to the original proposal of Taitel and Dukler (1976), the transition to the dispersed bubble flow pattern depends on the turbulence intensity of the liquid phase. Taitel and Dukler (1976) modeled the turbulence intensity based on the Levich (1963) approach, which is based on the velocity fluctuation estimated from friction factor correlation. In order to incorporate the effects of vibrations on the transition criterion, the vibration velocity was added to the fluctuation velocity, and the resulting transition criterion is given as follows:

$$\hat{T} > 4(1 - \alpha)^2 \left[ \frac{\alpha \pi}{\sin \gamma} - \frac{2Fr_{vi}^* \rho_l (1 - \alpha)}{\rho_l - \rho_v} \right] \quad (6)$$

where  $\hat{T}$  is given as follows:

$$\hat{T} = \frac{(dp/dz)_l}{g(\rho_l - \rho_v)} \quad (7)$$

and  $(dp/dz)_l$  is the frictional pressure drop evaluated for the liquid phase flowing in the channel.

### 3.4 Flow pattern maps

Figures 1 to 3 show the flow pattern maps for air-water flow at ambient temperature and atmospheric pressure in horizontal channels with internal diameters of 6, 10, and 20 mm, hence, comprising macro scale channels according to the Kew and Cornwell (1997) transition criterion. The condition of null  $A \cdot \omega$  corresponds to a static channel, hence the original proposal of Taitel and Dukler (1976). According to these figures, the imposition of vibrations on the channels implies in reduction of the  $j_l$  for most of the transitions, with a more pronounced effect for the transitions between smooth and wavy stratified, and between intermittent and dispersed flow patterns.

In fact, imposing tube vibration can induce the transition from smooth to wavy stratified pattern even for null velocity, as shown by Gaponenko *et al.* (2015). Therefore, the combination of both effects provides an earlier transition to wavy flow pattern.

Similarly, imposing vibrations on the channel increases the turbulence intensity favoring bubble breakup, therefore, anticipating the transition to a dispersed flow pattern. This result disagrees with the findings of Hibiki and Ishii (1998), who concluded that the vibration of the channel induces bubble coalescence. Nonetheless, as will be discussed in the next section, an experimental campaign is being performed for the validation or adjustment of the present method.

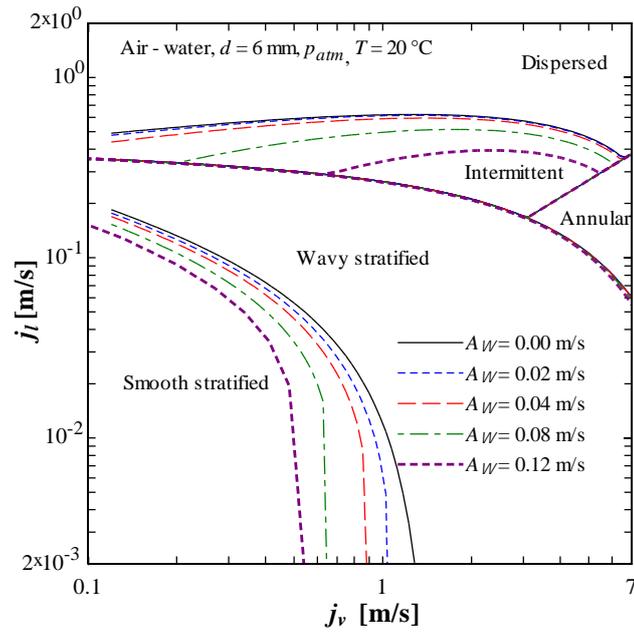


Figure 1. Flow pattern map for air-water flow in a horizontal 6 mm ID channel.

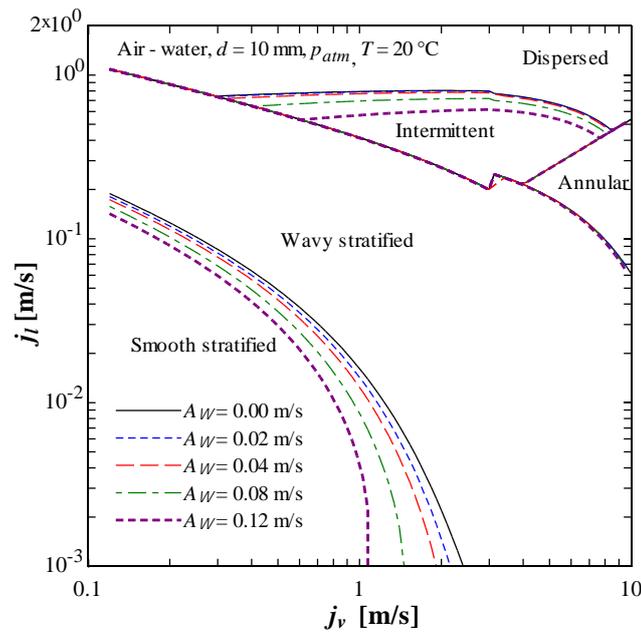


Figure 2. Flow pattern map for air-water flow in a horizontal 10 mm ID channel.

By comparing Figures 1 to 3, it can be concluded that the channel diameter does affect the transition condition, but the relative effect of the vibrations on the transition seems to be independent of the diameter.

Another important aspect to be considered in the future developments of this study is related to the channel scale. In the case of micro-scale channels, the buoyancy forces are suppressed due to the predominance of surface tension forces, as discussed by Kanizawa and Ribatski (2021). Consequently, another basic model should be adopted to account for these effects, such as the flow pattern predictive method proposed by Barnea *et al.* (1983).

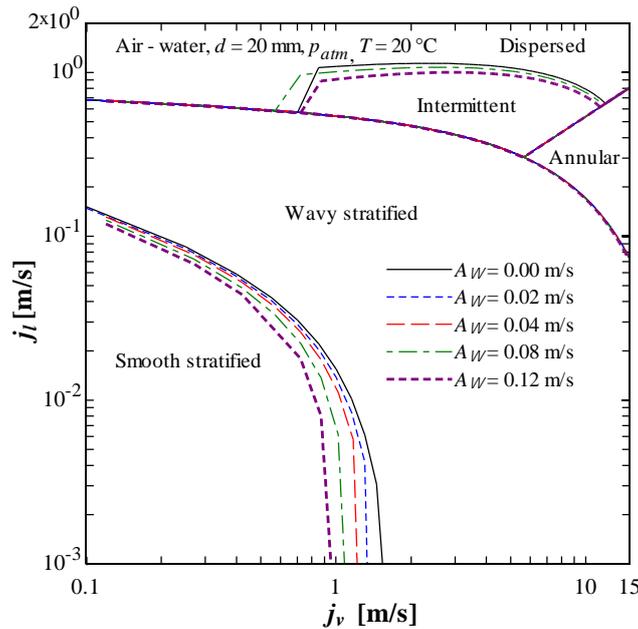


Figure 3. Flow pattern map for air-water flow in a horizontal 20 mm ID channel.

#### 4. EXPERIMENTAL FACILITY AND PROCEDURE

The experimental facility designed and under construction consists of a water loop with the injection of air, as depicted schematically in Figure 1. A centrifugal pump is used to propel the water from the reservoir, which is directed to the flow measuring section that consists of 4 rotameters with different ranges installed in parallel, then it is directed to the mixer and test section, and returns to the reservoir. The reservoir acts as a gravitational separator and is open to the atmosphere. Air is supplied by a compressed air line available in the laboratory, has the pressure adjusted by a pressure regulating valve, and is directed to the flow measuring section that consists of three rotameters with different ranges, and then it is directed to the flow mixer.

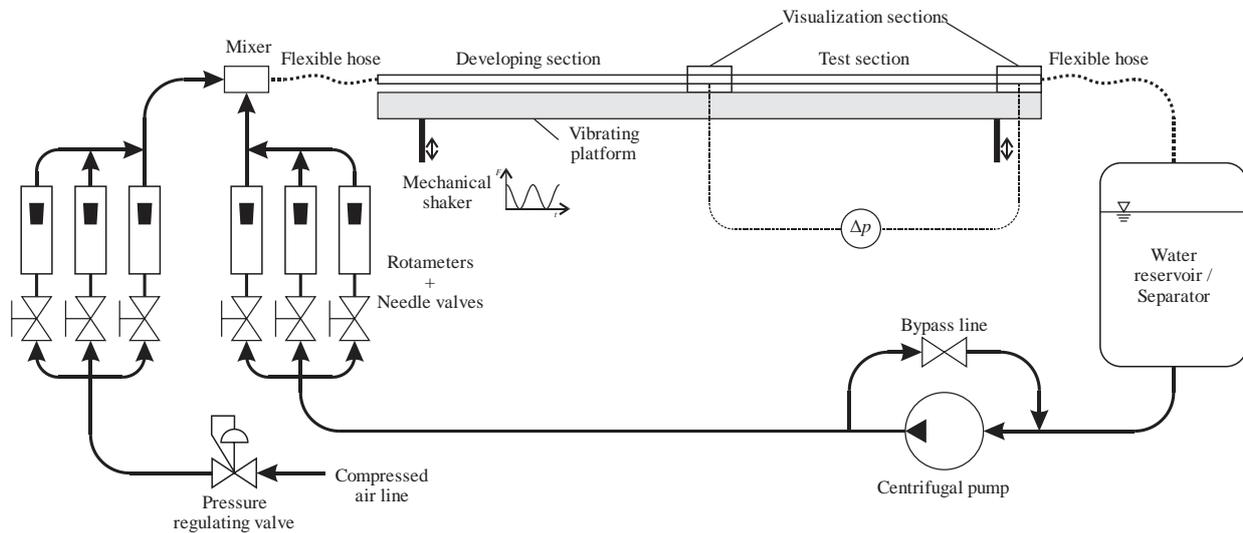


Figure 4. Schematics of the experimental loop.

A centrifugal pump Dancor CP-4R ½ cv is used to propel the water from the reservoir, and it is actuated by a frequency inverter model Danfoss VLT Micro Driver FC 51 with a nominal capacity of 1.5 kW, and a by-pass line is used to recirculate part of the flow rate, aiming to help in adjusting the flow rate. The water rotameters have a nominal uncertainty of  $\pm 5\%$  of the measured value, and the fine adjustment of the flow rate is performed by manipulating gate valves. More than one rotameter is used to comprise the entire flow rate desired for the experimental campaign.

In the case of the air setup, compressed air is supplied by a compressed air line available in the laboratory, and has the pressure adjusted by a ¼" pressure regulating valve to stabilize it for the measuring section. The measuring section consists of three rotameters installed in parallel with a nominal uncertainty of  $\pm 5\%$  of the measured value, with a distinct measuring range to comprise the entire flow rate, and controlled by an embodied needle valve to adjust the flow rate.

The mixer consists of a T connection installed upstream of the test section, where the air is injected in the downward direction to reduce the tendency of water backflow to the air line. The mixer is connected to the test section by a flexible hose made of silicone rubber with an internal diameter similar to the one in the test section. Similarly, the test section outlet is connected to the liquid reservoir and phases separator by a flexible hose. The liquid reservoir is a vessel open to the atmosphere with an internal capacity of 50 L.

The test sections consist of acrylic tubes with internal diameters of 3, 6, and 10 mm, 1.0 m long, and with visualization sections installed in the middle of the length and close to the outlet, as depicted in Figure 2. The components were cut with a laser machining process, and assembled by acrylic glue by a service provider. The setup counts with two pressure taps to measure the pressure drop along the test section. A flow-developing section is set in the first half of the test section, aiming to reduce the entrance effects.

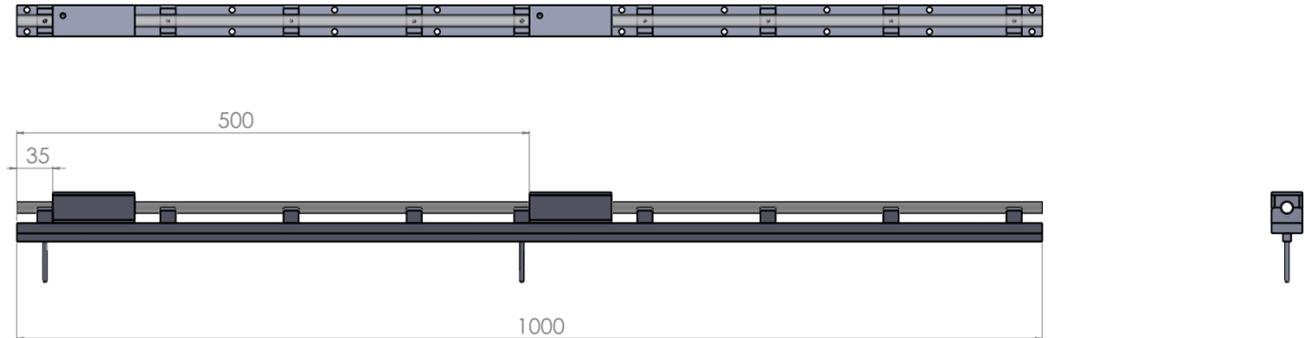


Figure 5. Schematics of the test section with an internal diameter of 10 mm. Flow direction from the right to the left.

The test sections will be installed on aluminum structural bars to provide the necessary rigidity to maintain a rigid body movement during vibrations, reducing eventual flexible body modes. The selected structure is provided by Famak with nominal dimensions of  $30 \times 30$  mm, and inertia momentum  $I$  of  $3.47 \text{ cm}^4$ . The aluminum profile weighs  $0.93 \text{ kg/m}$ , and the estimated mass of the acrylic assembly filled with water is up to  $1.0 \text{ kg}$ . For Young modulus  $E$  of  $68.9 \text{ GPa}$  and assuming a bi-supported beam, the natural frequency of the first mode is given as follows:

$$f_{n1} = \frac{1}{2\pi} \sqrt{\frac{E \cdot I}{4.73^4 L^4 m}} \quad (8)$$

where  $L$  is the distance between the supports, assumed as  $1 \text{ m}$ , and  $m$  is the mass per length, assumed as  $2 \text{ kg/m}$ . Based on this relationship, a frequency of  $123.1 \text{ Hz}$  is obtained, which is higher than the planned operational frequency of  $70 \text{ Hz}$ .

The vibration excitation system consists of a pair of electromagnets with  $100 \text{ N}$  of nominal force for  $24 \text{ V}$ , using an amplifier and a signal generator Minipa MFG-4202. The test section support will be installed via cylindrical rods using pillow blocks to allow one degree of freedom, supported by helicoidal springs with constant to result in frequencies higher than  $100 \text{ Hz}$ .

It is planned to perform experiments for gas superficial velocities between  $0.1$  and  $10.0 \text{ m/s}$ , and liquid superficial velocities between  $0.01$  and  $2.00 \text{ m/s}$ , which would result in flow patterns ranging from stratified to annular, for horizontal and vertical flows (Taitel and Dukler, 1976, Barnea *et al.*, 1983). It is planned to perform experiments for frequencies ranging between  $1$  and  $70 \text{ Hz}$ , and acceleration amplitude up to  $20 \text{ m/s}^2$ . The vibration frequency and amplitude will be measured by a pair of accelerometers MPU-6050 based on the Arduino platform, and the pressure drop will be measured by an Omega PMD75 differential pressure transducer with a measuring range of up to  $1''$  of  $\text{H}_2\text{O}$  ( $250 \text{ Pa}$ ) available in the laboratory.

The flow patterns will be identified based on a subjective approach (Kanizawa and Ribatski, 2021) capture with the help of a Canon EOS R10 camera, with a maximum frame rate of  $23 \text{ fps}$ , and a macro lens Canon EF 100 mm  $f/2.8\text{L}$  Macro, with a remote trigger to reduce the eventual influence of manipulations.

The test sections consist of parts of the experimental tube enclosed by a parallelepiped box that will be filled with water and sodium iodate to match the refractive index (Bai and Katz, 2014).

## 5. CONCLUSIONS

This study addresses a theoretical analysis of the effect of forced vibrations on flow pattern transition for gas-liquid flow in horizontal channels. For such analysis, the classical Taitel and Dukler (1976) predictive method was modified based mainly on the findings of Gaponenko *et al.* (2015). The following conclusions can be addressed:

- The flow pattern transition criteria were modified by including the effects of channel vibration by considering the modified vibrational Froude number, which includes the effect of vibration parameters, channel diameter, and flow characteristics.
- Based on these modifications, a new methodology was proposed and compared with the classical method for the static test section.
- By comparing the estimated transitional values for channels with internal diameters ranging between 6 and 20 mm, it can be concluded that the liquid superficial velocities correspond to the transitions reduced with the increment of vibrations amplitude or frequency. This effect is more pronounced for the transitions between smooth and wavy stratified flow patterns and between intermittent and dispersed flow patterns. On the other hand, the effect of the vibrations on the wave growth is negligible.
- An experimental facility is under construction to validate or adjust the proposed method, including channels of micro and macro scales.

## 6. ACKNOWLEDGEMENTS

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