19th Brazilian Congress of Thermal Sciences and Engineering
November 6th–10th, 2022, Bento Gonçalves - RS - Brazil

ENC-2022-0538
Experimental investigation of bubble turbulent fragmentation in a centrifugal pump

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Abstract. *The present work studies the dynamics of bubble coalescence and breakup in centrifugal pumps. This is a problem of special interest for the design of phase separators. The performance of centrifugal pumps under the action of gas-liquid mixtures has been vastly discussed in the literature. Those papers are prodigal in assessing the impact of the gas fraction on several pump characteristics. One aspect that is not often dressed is the impact of these equipment on bubble fragmentation. The high levels of turbulent kinetic energy in a centrifugal pump have a direct influence in the stability and uniformity of the flow field, promoting changes in the flow patterns that may be difficult to predict. Bubble breakup may contribute to unexpected changes in phase configurations and diameter distributions and can have serious effects on the performance of phase separators. The experimental facilities consist of a volumetric pump acting as a booster, a compressor, a commercially available centrifugal pump to be studied, a intermediate separator reservoir, two flow observation window apparatus. Flow rate sensors for the liquid and gas phases were used in conjunction with temperature and pressure sensors for the appropriate measurement of fluids properties. The flow closed circuit was constructed in transparent piping allowing for the employment of Shadow Sizing technique to measure the disperse phase under high speed stroboscopic image acquisition. Care was taken to allow a flow development length on the inlet of the studied pump and the positioning of pressure sensors along the bench to allow the correction of gas volumetric flow rate. The work, in particular, discusses the use of a simple phenomenological theory based on dimensional analysis for the development of a simple expression capable of expressing the mean output diameter of bubbles in terms of the turbulent dissipation rate, the rotation and the diameter of the impeller. The arguments are similar to those of the early literature and are validated through experimental data obtained through the Shadow Sizing technique. The flow conditions consider the four expected flow patterns inside a two-phase gas-liquid pump. The volumetric gas-fraction is varied up to 35%.*

Keywords: *centrifugal pump, multiphase flow, bubble and slug pattern, turbulent energy*

1. INTRODUCTION

In many industrial applications centrifugal pumps are required to operate under gas-liquid loading. The presence of gas provokes instabilities in the pump operation, which may lead in the limit of high gas fractions to catastrophic performance degradation. The performance of centrifugal pumps under the action of gas-liquid mixtures has been vastly discussed in the literature (see, e.g., Monte Verde *et al.* (2017)). The papers are prodigal in assessing the impact of the gas fraction on several pump characteristics, in particular, on the promoted head. The works also aim at correlating the expected pump performance to the four typically identified flow patterns.

One aspect, however, that is not often addressed is the impact of centrifugal pumps on bubble fragmentation. The high levels of turbulent kinetic energy in a centrifugal pump have a direct influence in the stability and uniformity of the flow field, promoting changes in the flow patterns that may be difficult to predict. Bubble breakup may contribute to unexpected changes in phase configurations and diameter distributions and can have serious effects on the performance of phase separators.

The purpose of the present work is to assess the global detrimental effects of centrifugal pumps on bubble breakup.

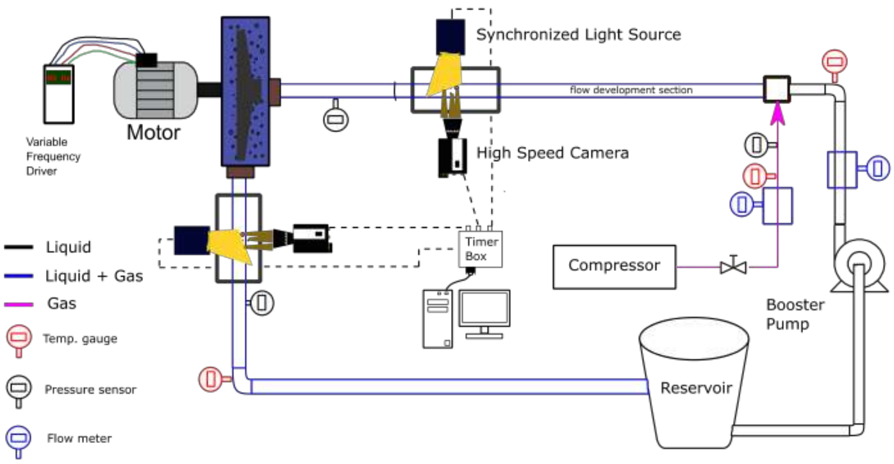

Figure 1: Schematic drawing of the experimental setup.

This work investigates the use of a dimensionless group to correlate bubble distribution in the exit region of a centrifugal pump to the income bubble distribution. The arguments are very simple and are based on the reasoning of Hinze (1955) and Kolmogorov's scales for velocity and length.

The work shows how a combination of inlet conditions (gas and liquid flow rates, rotational speed) leads to different flow patterns. One particular concern investigated here is the description of slug flow breakup. For bubbly flow patterns, the maximum diameter of a bubble subjected to the field of an centrifugal pump can be shown to be proportional to $\omega^{6/5}$ (ω = rad.s^{-1}). For slug flows this relation requires validation.

To understand the flow pattern formation and the changes in bubble features, optical visualization is used. Results are shown for liquid flow rates varying from 1 to 3 m^{3}h^{-1}, gas fractions between 0.5 to 35% and two rotation velocities.

2. Experimental Facilities

The experimental facilities are illustrated in Fig. 1. The flow loop was designed to acquire global (absolute pressure, flow rates and temperature) and local (mean diameter distributions, bubble velocities) properties in the inlet and outlet regions of the pump. All connecting pipes are transparent (19 mm ID). The centrifugal pump is a single stage Dancor CAM-W6 1 HP, with impeller diameter of 136 mm, nominal speed of 60Hz and the maximal head of 35 mca. The experimental bench consists of a water reservoir, a progressive cavity pump (PCP), a compressor, an air-water mixer and a centrifugal pump. An electromagnetic flow meter for the continuous phase and a variable area flow meter for the dispersed gas were used.

The Shadow Sizing technique was applied together with a SpeedSense M310 camera. Frame acquisition frequencies were between 400 Hz and 1400 Hz. The DynamicStudio 2015a software was used to improve contour identification and processing of images.

3. Results

3.1 Head curves and global data results

The two dimensionless groups $\pi_1 = Q/(\omega D_{imp}^3)$ and $\pi_2 = gH/(\omega^2 D_{imp}^2)$ are used to illustrate the head curves for different rotation speeds (Figs. 2a-b). Where Q is the volumetric flow rate, ω the angular speed, D_{imp} the impeller diameter, H the head and g the gravity acceleration.

The curves show the effects of gas flow ratio, $\beta = Q_G/(Q_L + Q_G)$, where Q_L is the liquid flow rate and Q_G the gas flow rate in m^{3}h^{-1}, on the head curves for 20 Hz (1173 rpm) and 35 Hz (2053 rpm). Surging and gas blockage behavior are readily observed. For different β's and rotation speeds, a critical π_1 is possible to observe, whereby two distinct plateaus mark the transition between the gas pocket pattern and separated flow inside the pump (Monte Verde *et al.* (2017)). π_1 and π_2 are correlated quantities through parameters β and ω.

3.2 Flow patterns in two-phase pipe flow

Figures 3a-d and 4a-d show images upstream and downstream the pump for frequencies of 20 and 35 Hz for both bubble and slug flows. Figs. 5 and 6 present the size and velocity distributions for small and long bubbles in the inlet of the pump, and small bubbles in the outlet. For bubble flow, the inlet mean diameters for both frequencies are respectively 1 and 1.3 mm. The outlet mean diameters are about 0.4 mm. For slug flow, the inlet Taylor bubbles have mean lengths of

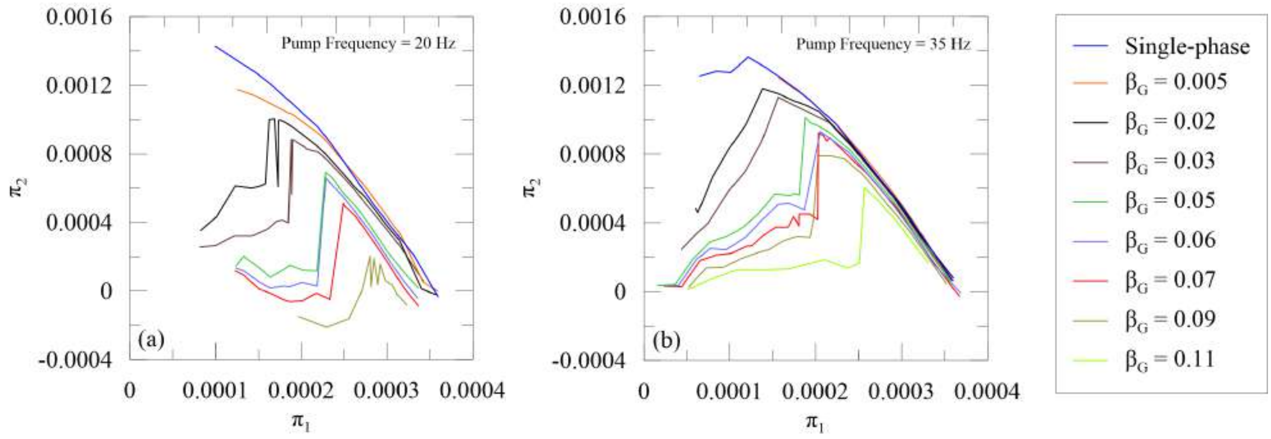

Figure 2: Experimental piezometric head curve for different gas ratios and rotational speeds of 20 Hz (a) and 35 Hz (b). Data on single-phase water flow is also shown for comparison.

100 mm (20 and 35 Hz). The liquid slug bubbles are 0.3 mm in mean diameter at pump inlet. For both flow conditions, the outlet bubbles show a mean diameter of about 1 mm.

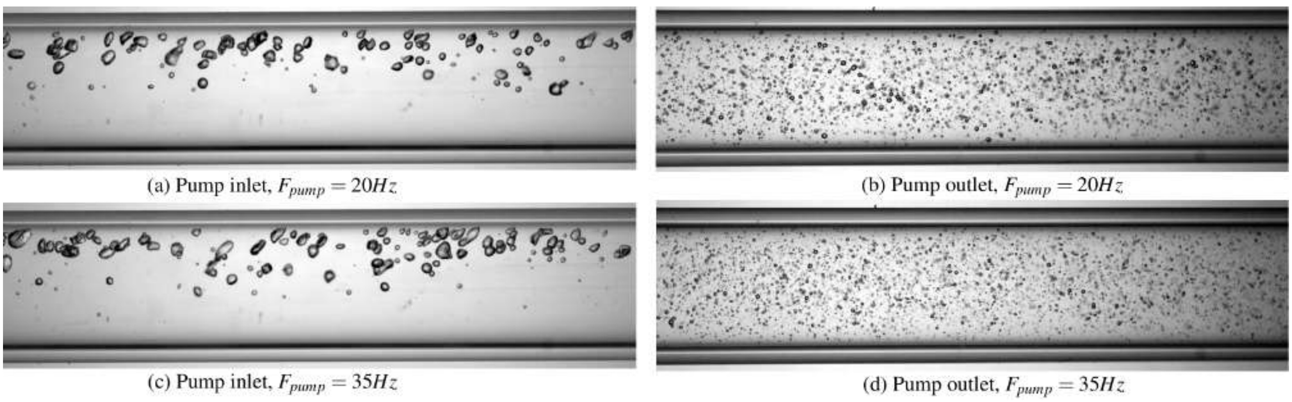

Figure 3: Flow pattern in the inlet and outlet regions of an ESP for β = 0.005.

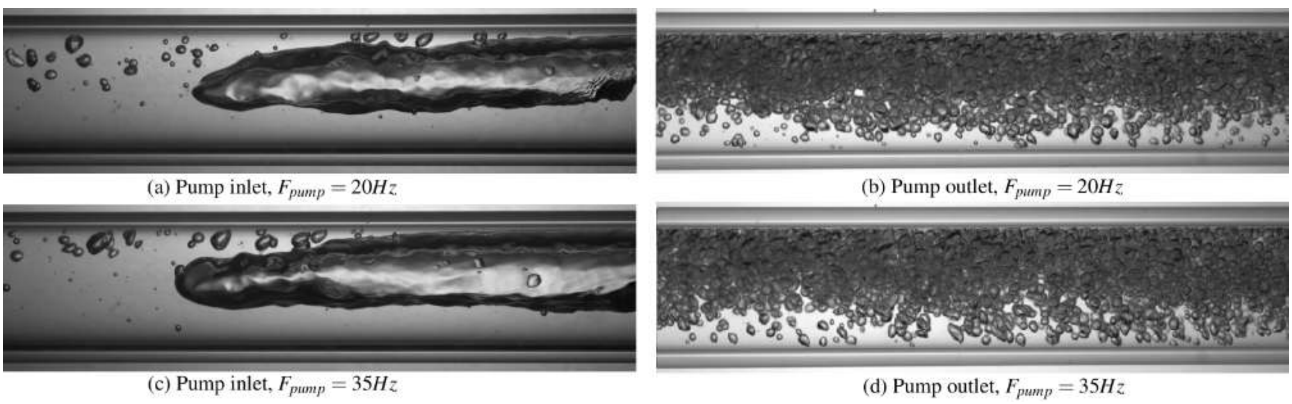

Figure 4: Flow pattern in the inlet and outlet regions of an ESP for β = 0.35.

3.3 Bubble diameter prediction

In the classical theory of Hinze and Kolmogorov, scaling arguments lead to an expression for the maximum permissible bubble diameter ($D_{b_{max}}$) in terms of a critical Weber number, properties of the fluids and the dissipation rate of the turbulent kinetic energy (ε_{pump}) :

$$D_{bMmax} = \left(\frac{We_{\text{critical}}}{2}\right)^{\frac{3}{5}} \left(\frac{\sigma}{\rho_L}\right)^{\frac{3}{5}} \varepsilon_{pump}^{-\frac{2}{5}} \tag{1}$$

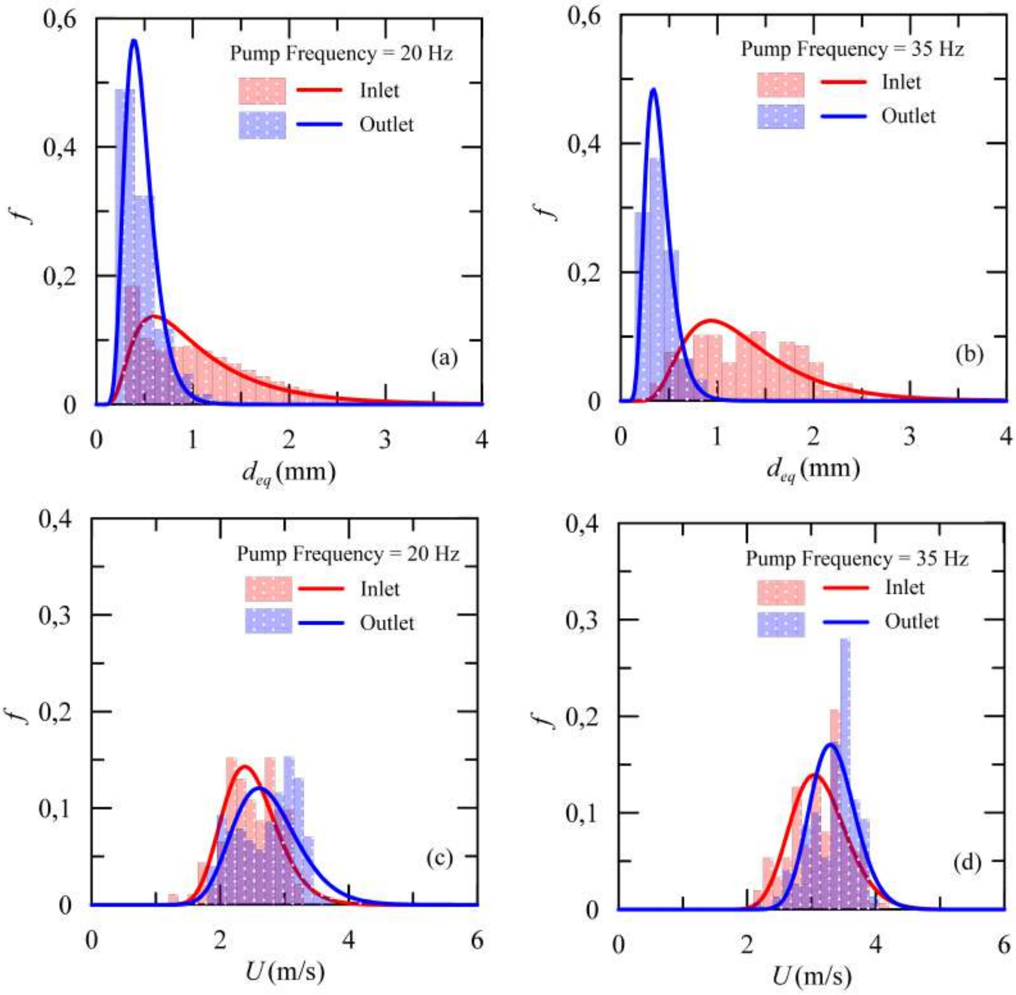

Figure 5: Equivalent diameter and velocity distribution statistics for bubbly flow passing through a centrifugal pump, downstream and upstream data for β = 0.005.

where, for our specific case:

$$\varepsilon_{pump} = \frac{\dot{W}_{shaft} - \dot{W}_h}{\rho_M V_{pump}} = \frac{\dot{W}_{electrical}\eta - \Delta P Q_M}{\rho_M V_{pump}} \tag{2}$$

Form the above equations the dimensionless group can be constructed:

$$\pi_4 = \frac{\varepsilon_{pump}}{\omega^3 D_{imp}^2}, \quad D_{imp} = \text{impeller diameter} \tag{3}$$

For pipe flow, Hesketh et al.(1987) suggest an alternative equation to Eq. (1):

$$D_{b_{maxHesketh}} = 1,36 We_{\text{critical}}^{0,6} \left(\frac{\sigma^{0,6}}{\rho_L^{0,3} \rho_G^{0,2} \mu_L^{0,1}} \right) \frac{D_{tube}^{0,5}}{U_{SL}^{1,1}} \tag{4}$$

Equation (4) can be used to correlate the average maximum bubble diameter in Two-Phase Pipe Flow with predictions of Hesketh et al.'s equation. The results are shown in Figure 7 for various flow conditions. Fig. 8 shows $D_{b_{AvgMax}}$ in the pump outlet as compared to Hinze (1955). Fig. 8 shows a large data dispersion, but considering the diversity of conditions to which Eq. (1) was applied including bubble and slug flow patterns this would be expected. The results, however, are promising.

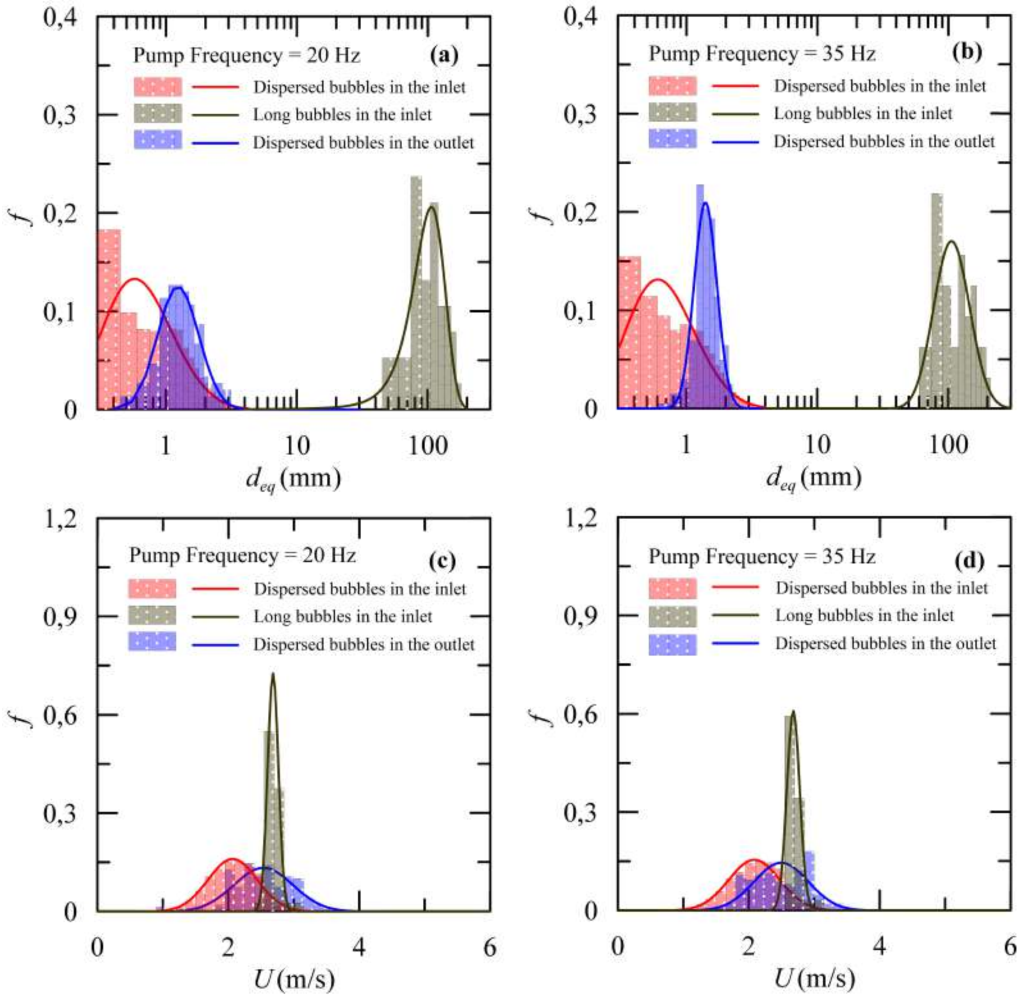

Figure 6: Equivalent diameter and velocity distribution statistics for slug flow passing through a centrifugal pump, downstream and upstream data for $\beta = 0.35$.

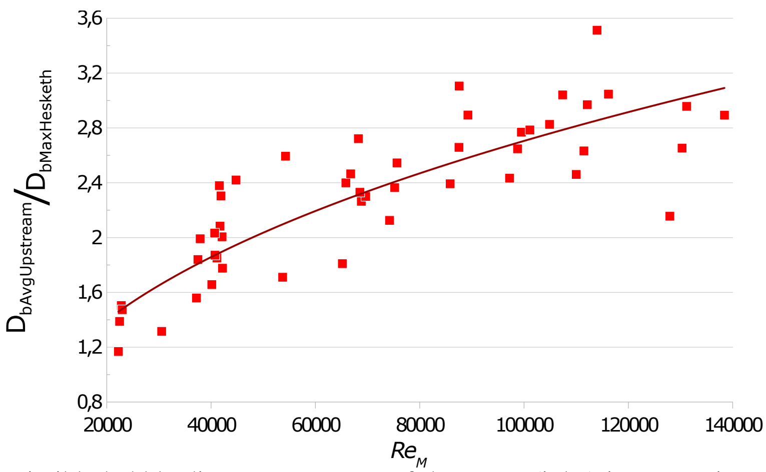

Figure 7: Maximum permissible bubble diameter upstream of the pump (inlet) in comparison to Hesketh *et al.* (1987) (Carneiro, 2021).

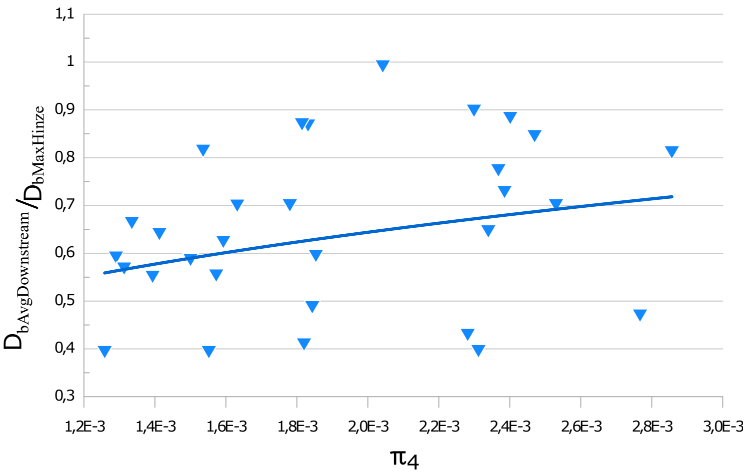

Figure 8: Maximum permissible bubble diameter downstream of the pump (outlet) in comparison to Hinze (1955) (Carneiro, 2021).

4. ACKNOWLEDGEMENTS

The authors would like to thank Petrobras, ANP, FAPERJ and CNPQ for the financial support during this research.

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