Oscillatory flows in jet pumps
Towards design guidelines for thermoacoustic applications

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Thermoacoustic engines are an interesting alternative to conventional heat engines (such as Stirling engines) due to the absence of moving parts in the hot region and the small temperature difference required to operate. These engines can provide a durable solution in, for example, waste heat recovery applications. Using a traveling wave based configuration, consisting of a toroidal geometry, thermal-to-acoustic efficiencies of up to 30% have been obtained. However, the traveling wave configuration has a major disadvantage: due to the closed looped geometry a time-averaged mass flow, known as “Gedeon streaming”, can occur. This type of acoustic streaming can lead to a drastic reduction in efficiency or even prevent the engine from running. Therefore, control of Gedeon streaming is essential in the development of traveling wave thermoacoustic engines.

A solution to avoid Gedeon streaming is the application of a jet pump, which is a component with one or more tapered holes as indicated in Figure 1. The oscillatory flow through such an asymmetric geometry results in a time-averaged pressure drop across the jet pump. By balancing this time-averaged pressure drop with the pressure drop that exists across the regenerator of the thermoacoustic device, Gedeon streaming can be suppressed. In this research, the oscillatory flow in jet pumps is analyzed. The jet pump performance in terms of the time-averaged pressure drop and acoustic power dissipation is studied as a function of the jet pump geometry, the operating frequency and the amplitude of the acoustic wave. Five different studies are performed within this research.

Using a two-dimensional axisymmetric computational fluid dynamics (CFD) model, the laminar oscillatory flow through single-hole jet pump geometries is simulated. Four different flow regimes are distinguished based on the flow features identified, such as vortex ring formation and flow separation. These four flow regimes are depicted in Figure 2. The occurrence of the flow regimes is subsequently linked to the simulated jet pump performance. The jet pump diameter, taper angle, length and edge curvature are varied independently and scaling parameters are introduced to predict the performance and flow regime as a function of the jet pump geometry. Based on this, design guidelines for jet pumps in laminar oscillatory flows are formulated.

Flow separation from the inner jet pump wall is shown to have a large negative impact on the performance of a jet pump. In laminar oscillatory flows, the onset of flow separation is directly related to the acoustic displacement amplitude in combination with the jet pump diameter and taper angle. This onset value is confirmed experimentally using hot-wire anemometry in both laminar and turbulent oscillatory flows. The process of flow separation is characterized in a separate study.

Figure 1: (a) Jet pump with parameters that define its geometry (not to scale). Bottom dashed line indicates center line, top solid line indicates outer tube wall. (b) Isometric representation of $\alpha = 15^\circ$ jet pump sample.
Four different flow regimes are distinguished based on the Keulegan-Carpenter numbers $KC_L$ and $KC_D$ using the instantaneous vorticity fields $\nabla \times \mathbf{u}$ [1/s] at $t = t_{max}$ (top) and streaming velocity fields $u_2$ [m/s] (bottom) around the jet pump for the $\alpha = 7^\circ$ geometry, $f = 100$ Hz. Black line in streaming velocity field indicates transition from positive to negative velocity. From: J.P. Oosterhuis, S. Bühler, D. Wilcox, and T.H. van der Meer, J. Acoust. Soc. Am. 137(4):1722-1731, 2015

numerical study and a design adjustment is proposed that can significantly reduce the flow separation. By introducing a smooth curved transition from the jet pump small opening towards its tapered surface, the onset of flow separation is shifted to larger displacement amplitudes and the duration of the separated flow is reduced. This greatly enhances the effectiveness and robustness of jet pumps in laminar flows. To make the proposed jet pump designs more compact without affecting their performance, it is shown to what extent the big opening diameter can be reduced before local minor losses influence the jet pump performance.

The effect turbulence has on the performance of a jet pump is investigated in an experimental study. By measuring the time-averaged pressure drop and acoustic power dissipation, it is observed that the large performance decrease induced by flow separation is mitigated in turbulent flows. Instead of a rapid decrease in the dimensionless time-averaged pressure drop after the onset of flow separation, the dimensionless time-averaged pressure drop has the tendency to stabilize in the turbulent flow regime. Hot-wire anemometry is used to characterize the level of turbulence. The critical Reynolds number for oscillatory pipe flows is found to be a correct predictor for turbulence in jet pumps as well.

For compact thermoacoustic devices it is important to design a compact jet pump geometry with a minimal reduction in performance. Decreasing the length of a jet pump by increasing its taper angle is shown to directly facilitate the occurrence of flow separation and should be avoided. Alternatively, the size of a jet pump can be reduced by employing multiple smaller orifices instead of one single hole. Doing so largely reduces the jet pump length while both the total cross-sectional area and the taper angle remain unchanged. The effect of this design approach on the jet pump performance is investigated experimentally. Although a significant performance decrease is measured when increasing the number of holes from 1 up to 16 holes, the time-averaged pressure drop remains much higher compared to compact geometries with large taper angles. The decrease in time-averaged pressure drop for multiple hole jet pumps is shown to be caused by the smaller diameter of the individual orifices rather than to the interaction of flow between adjacent orifices.

The studies in this research show the relation between oscillatory flow features and the performance of jet pumps. Based on this, jet pump design guidelines have been formulated for laminar oscillatory flows. Flow separation is identified as a main source of performance loss in jet pumps and can be avoided by introducing a smooth transition to the tapered inner surface. Compact jet pump designs can be realized by using multiple smaller tapered holes, but this is accompanied by a slight reduction in performance due to the smaller diameter of the individual holes. Identifying and understanding the flow phenomena in jet pumps is shown to be the key to more reliable design calculations for jet pumps in thermoacoustic applications.

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