Numerical investigations on pressure wave refrigerators for sizing the dump tank and studying its effect on the operating frequency at first peak efficiency

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Abstract

A pressure wave refrigerator (PWR) is an unsteady flow device that uses shock waves and rarefied waves to generate refrigeration. The working principle of a PWR is similar to that of a standard shock tube. High-pressure gas is injected periodically into a stationary receiving tube through a rotary valve. A shock wave is formed at the injection point that moves forward, and at the same time, a rarefied wave travels backwards, producing refrigeration. In this paper, a two-dimensional numerical model is developed using Ansys Fluent^{TM} to analyse a PWR. The numerical model is validated with the experimental data available in the literature. The performance of PWR is adversely affected by the reflected shock wave. A dump tank with a restrictor is placed at the end of the receiving tube to attenuate the reflected shock waves. The effects of the size of the dump tank in terms of the volume of the stationary receiving tube are studied for different tube lengths and pressure ratios. These results will help us better understand the behaviour of a PWR and the critical issues in designing such a system.

Introduction

The energy transfer across a shock wave is utilized in many applications, including gas compression, supercharging in diesel engines, power generation, pulse detonation, production of refrigeration as well as in biological and medical applications. The PWRs are a class of machines that use shock waves and expansion waves for production of refrigeration. Compared with turbo-expanders, a PWR can operate at a much lower rotational speed and at lower flow rates. Moreover, these are cheaper, simpler in design and operationally more reliable. PWRs are effectively used in applications such as gas separation, cryogenic grinding, and cryogenic refrigeration.

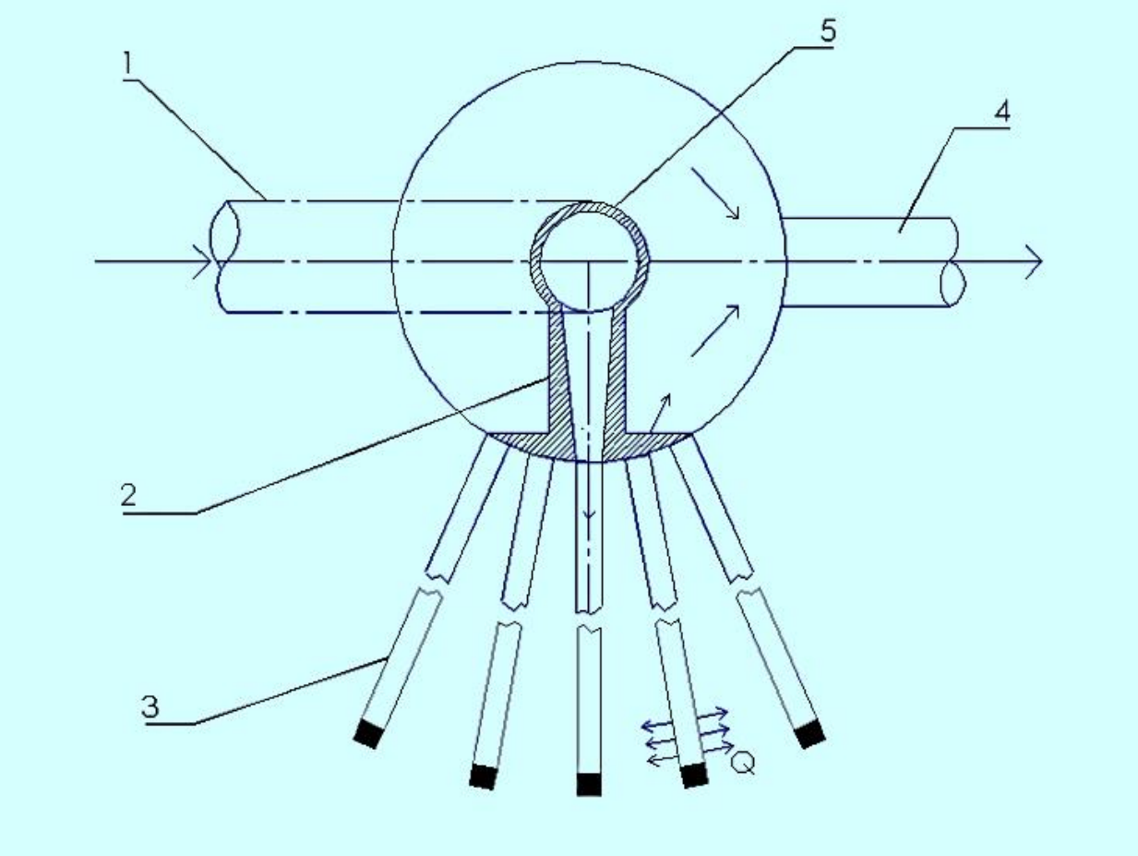


Fig 1: Typical arrangement of a PWR (1-gas entry, 2 – jet, 3-receiving tubes, 4-outlet, 5-hollow shaft with jets.)

Numerical analysis

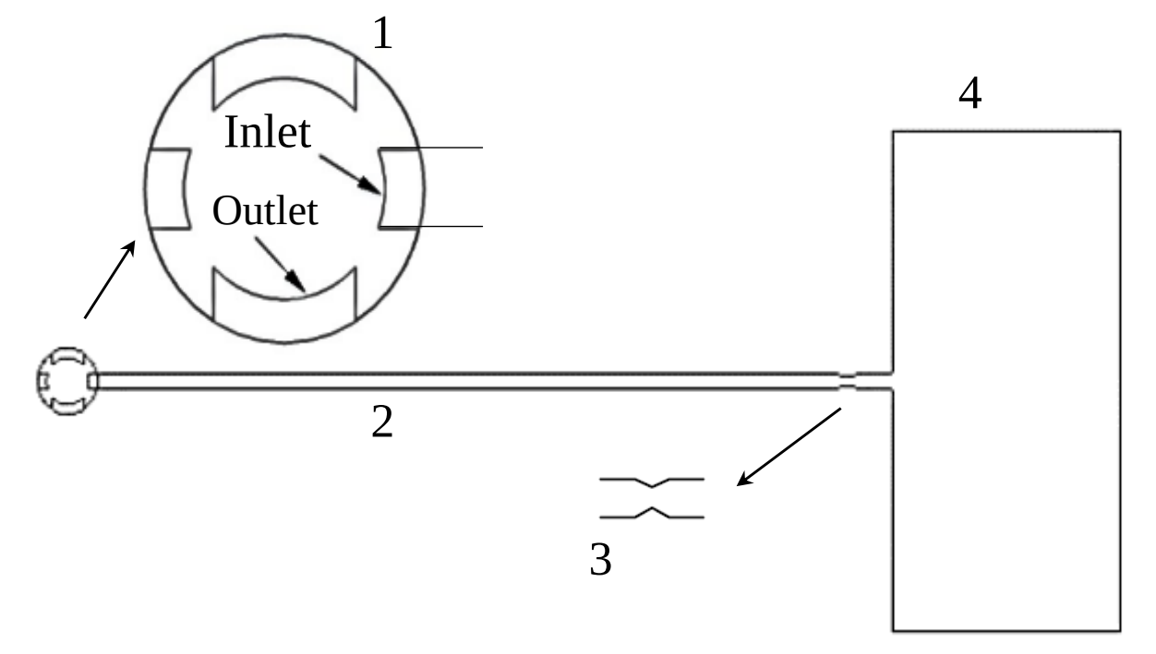


Fig 2: Geometry used in the model; 1-rotating gas distributor; 2-stationary receiving tube; 3- restrictor; 4-dump tank

Geometry

- It consists of a rotating gas distributor and a static tube connected with a rotor-stator interface.
- A thin gap of 0.1 mm is maintained between the rotating gas distributor and the surrounding static body.
- Preceding the dump tank, a restrictor, referred to as a shrink, is employed to enhance shock wave attenuation, aligning with observations made by Hu et al. (2008).

Solution methodology

- ➢ Governing equations are solved by using finite volume formulation in Ansys Fluent^{TM} (v 21.2) platform.
- ➢ The continuity equation was solved using the SIMPLE algorithm.
- ➢ Realizable *k-ε* turbulent equations are solved in a 2-D model.
- ➢ Coupling between rotating fluid and stationary fluid is done through a sliding mesh.
- ➢ A very fine mesh size of 5x10^{-6}m has been used, which is obtained through grid independence studies

Results and discussions

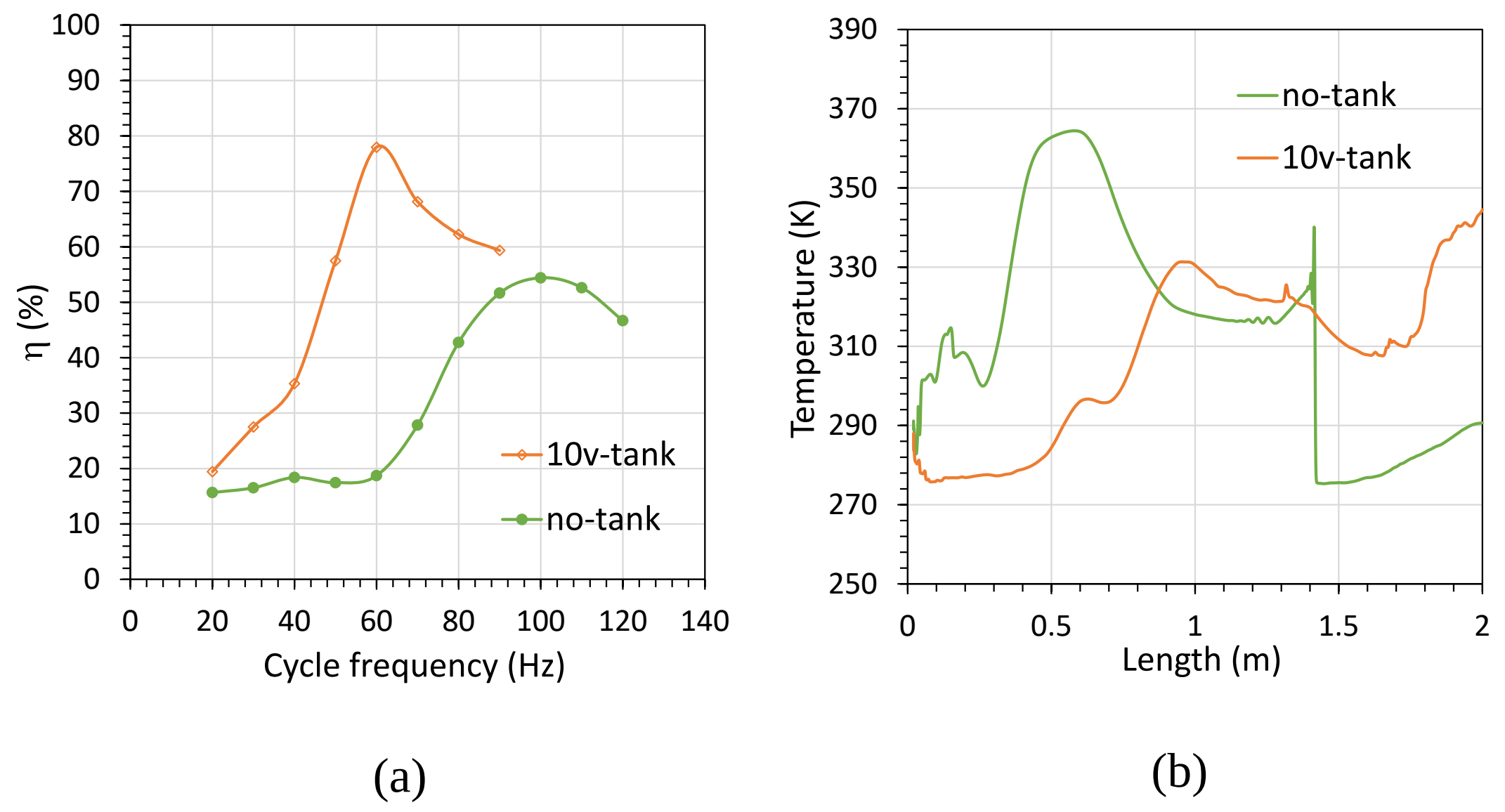
- ○ The performance of a PWR is evaluated in terms of the isentropic efficiency of the system and the temperature profile along the length of the stationary receiving tube.

Isentropic efficiency (n_s)

$$\eta_s = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{1 - \frac{T_{avg}}{T_1}}{1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}}$$

Where T_{avg}, h, T and P denote the average temperature of the outlet gas, enthalpy, temperature and pressure of the gas. Subscript 1 and 2 refer to the states at the injection and exhaustion points respectively. γ is the specific heat ratio and h_{2s} is the expansion enthalpy.

Effect of dump tank



(a) (b)

L = Length of the receiving tube
d = Diameter of the receiving tube
v = volume of the receiving tube
PR= Pressure ratio

Fig 3 : (a) Isentropic efficiency vs cycle frequency and (b) Fluid temperature along the length of the receiving tube just before discharge for peak isentropic efficiency[L = 2 m, d= 10 mm, PR= 2, *60% cooling length and dump tank with 50% shrinkage before the dump tank].*

- ❖ The isentropic efficiency increases from 54% to 78 % with the attachment of a dump tank at the end of a 2 m receiving tube.
- ❖ The dump tank absorbs the shock wave and prevent the reflected shock wave to reheat the fluid in the receiving tube.

Variation of performance of PWR with dumping tank volume for different operating frequencies and lengths

- ❖ The efficiency of the PWR increases as the dump tank volume increases from 1v to 10v (v = volume of the receiving tube)
- ❖ The efficiency slightly decreases as the volume increases from 10v to 15v, and then it becomes asymptotic.
- ❖ For a dump tank of 10v volume, a maximum isentropic efficiency of 78% is achieved.

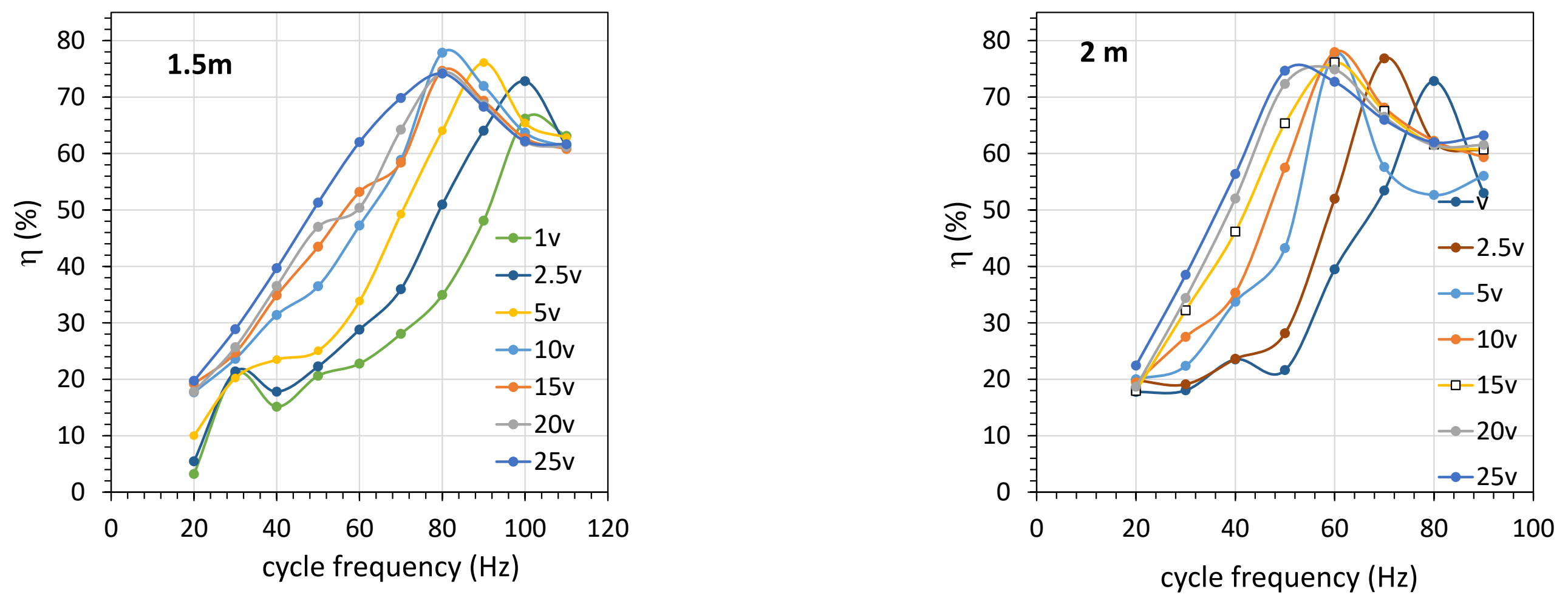


Fig 4 : Isentropic efficiency vs cycle frequency for volumes of the dumping tank, v =1, 2.5, 5, 10, 15, 20, and 25 times the stationary receiving tube volume

Variation of performance of PWR with dumping tank volume for different pressure ratios

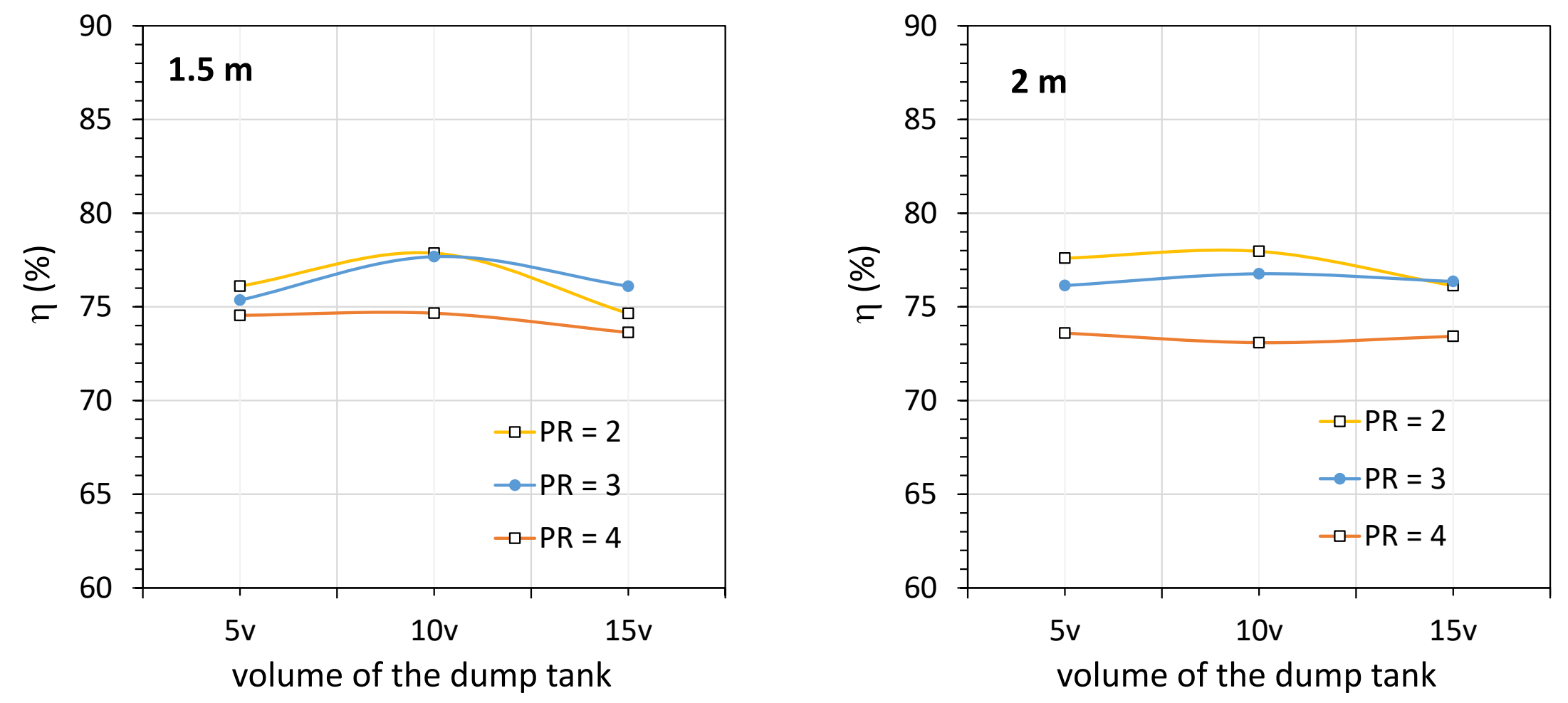


Fig 5: Isentropic efficiency vs pressure ratio

- ❖ At higher pressure ratios the efficiency of the system decreases for both 1.5 m and 2 m length tubes.
- ❖ A maximum efficiency is attained for a PR of 2 of around 78%.

Conclusions

- ❖ A dump tank with a restrictor just before the dump tank absorbs the shock wave and prevents it from reflecting back to the tube.
- ❖ A significant enhancement in isentropic efficiency is achieved with the dump tank.
- ❖ The size of the dump tank for maximum efficiency depends upon the volume of the receiving tube used.
- ❖ For a particular volume of the stationary tube used, a dump tank with 10 times the volume of the receiving tube (10v) results in maximum efficiency.
- ❖ The isentropic efficiency increases from 54% to 78 % with the attachment of a 10v dump tank at the end of a 2 m receiving tube.
- ❖ As the operating frequency of the PWR is changed, maximum isentropic efficiency is achieved for a particular frequency known as peak frequency.
- ❖ The peak in efficiency only depends on the length of the receiving and the size of the dump tank.
- ❖ The first peak frequency does not depend on the pressure ratio of the system.
- ❖ 80 Hz and 60 Hz are the first peak frequencies for 1.5 m and 2 m length tubes for a 10v dump tank.

References

1. Hu, D., Chen, S., Liu, H., Chen, Z., Zhu, C., 2006. Numerical and experimental study on contact face and shock wave motion in the receiving tube of gas wave refrigerator. J. Therm. Sci. 15 (4), 337-441.
2. Hu, D., Chen, S., Yang, J., Chen, Z., Dai, Y., Zhu, C., Liu, R., 2008. Study on gas and wave in a receiving tube. J. Thermal Sci., 17(2), 170–174.
3. Liu, P.Q., Zhu, Y.Q., Zhao, J.Q., Hu, D.P., Zou, J.P., 2013. Investigation and optimization of waves motion behavior in pressure oscillating tube. Exp. Therm. Fluid Sci. 50, 193-200.
4. Saito, T., Voinovich, P., Zhao, W., Shibasaki, K., Shibasaki, S.,Takayama, K., 2003. Experimental and numerical study of pressure wave refrigerator performance. Shock Waves 13, 253-259.
5. Shao, J., Bao, Y., Shen, Y., Feng, Y., Zhang, C., Gao, J., 1986. Experimental study of the influence of transient performance in pressure pulse tubes on isentropic efficiency of rotary jet expanders. Cryogenics 26, 634-636.
6. Zheng, M., Liu, X., Li, X., Fan, Y., X. Jiang, X., Li, X., Tu, J., 2018. Experimental study of the influence of some factors on the refrigeration efficiency of pressure wave refrigerator. COBEE Paper 066, 192–197.