Superheated Steam from Low-Temperature Waste Heat: A Brief Technical Overview of The Open Oscillatory Approach

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Introduction

Lost waste heat is global industry's largest operational inefficiency, and its energy remains largely untapped in most part because of systemic unfavourable electricity-to-gas price ratio which has slowed adoption of waste heat recovery (WHR) systems. The Icelandic engineering company Hydram Research has been developing and testing a novel large-scale WHR system, which leverages an open oscillatory approach where a multi-ton liquid piston is advantageously oscillated up and down to generate, compress and eject steam.

Methods

The system is composed of two hermetically sealed containers connected at the bottom *(Figure 1)*. The lower and wider tank (called side-tank) has an air pocket at the top acting as a gas spring maintaining the water's oscillation. The steam is repeatedly generated and subsequently compressed at the top of the taller and thinner pipe (called high pipe). During the system's operation the multi-ton warm liquid piston is intentionally oscillated between the two containers. Each oscillation takes ~2-3s and consists of the following three stages:

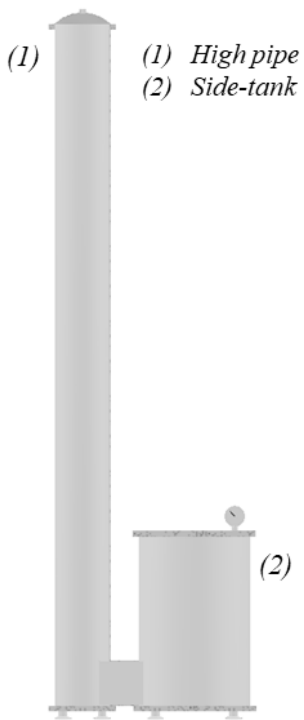

Figure 1: System layout

(i) Low pressure steam is evaporated at the top of the high pipe with rapid volume expansion (large bubble cavitation) when pressure there drops down to the water's evaporation pressure. The volume expansion and downward acceleration of the liquid piston is initially driven by hydrostatic instability. At its maximum downward velocity, it overshoots its equilibrium and starts to decelerate. At the same time, the water level in the side-tank increases, compressing the air pocket and augmenting the deceleration.

(ii) Once the water level in the high pipe reaches its lowest point in the oscillation the air pressure in the side tank is at its maximum, causing high hydrostatic instability. This accelerates the water upwards, compressing the newly formed steam. As the water moves up the high pipe, the water in the side-tank lowers, expanding the air pocket.

(iii) As the water's surface approaches the top of the high pipe again and the steam's pressure exceeds a predetermined limit, it is ejected into the steam header via an ejection valve. At the end of the ejection the water's surface will have reached its highest point, its starting position, and the process repeats.

The oscillation is excited and maintained by modulating the pressure in the side tank's air pocket using a rapid acting air piston which increases the pressure in the side tank when it's already high and then decreases it when it is at its lowest.

The most important aspect of the system's design is that the steam's energy is largely derived from the latent heat of the liquid column and not from the mechanical energy employed to maintain the oscillation. This effect is often referred to as evaporative cooling and will rapidly cool down the liquid piston if it is not continuously kept warm via a heat exchanger.

Results and Discussion

Hydram Research's newest prototype is 10.6 m (35 ft.) high, with 0.4 m (1.3 ft) high pipe diameter and a theoretical output of +100kWth. The first successful steam extraction took place in July 2025 since it has demonstrated promising performance generating and ejection superheated steam reaching temperatures up to 126°C (260°F) and pressures of up to 155kPa (22.5 psi abs.) with system water maintained at 60°C (140°F) (Figure 2). Tests in a full-sized prototype have demonstrated that it is indeed viable to compress and superheat low pressure steam using the same liquid column from which it was derived.

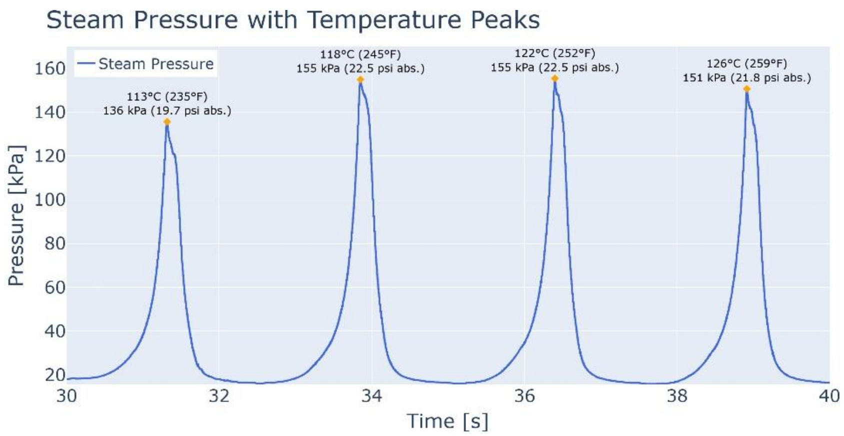

Figure 2: Steam temperature in the cavity with respect to time throughout one test cycle. Temperature sensor is located at the very top of the high pipe

It is worth noting that while this test was performed at 60°C (140°F), the system is highly flexible to source temperature. Although overall efficiency increases with increasing source temperature, current data suggests that energy recovery is likely economical down to about 20°C (68°F). In the wake of these promising results, work is ongoing to increase and measure the system's power output. The ongoing development will allow for a more detailed characterisation of the steam properties and system efficiency. Design of a larger 500kW-1MWth pilot installation will ensue.

Figure 3 illustrates how the system will be installed with the primary source of power being the low-grade waste heat from the facility running into the hottest vertical oscillator, exiting colder to the next oscillator etc. until it becomes uneconomical to extract more of the stream's waste heat.

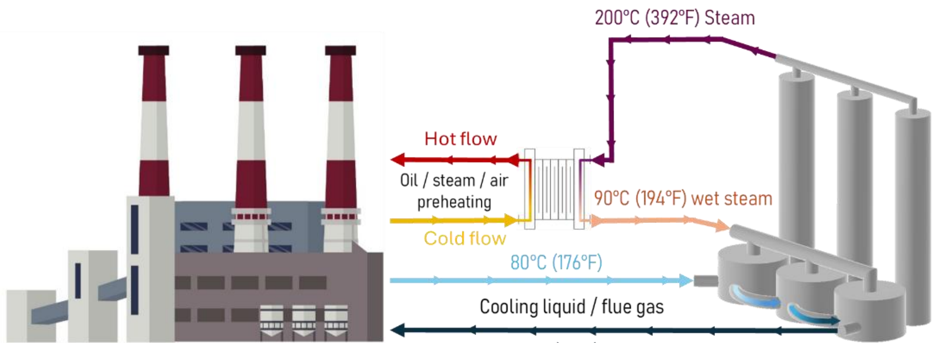

Figure 3: Diagram of Hydram Research's WHR system installed at an industrial facility (indicative figure).

Conclusion

As the demand for cost-effective solutions to increased energy efficiency is growing globally, initial testing of Hydram Research's WHR system has shown promising results with the first steam ejected from the system in July 2025. In those and subsequent tests the system the demonstrated ability to generate, compress and heat steam up to temperatures reaching 122°C (252°F) at 155kPa (22.5 psi abs.). Based on these positive results and proof-of-concept, work is ongoing to increase power-output, improve models and optimize the system's operation for it to robustly and efficiently convert warmth to superheated steam on an industrial scale.

For further information we refer to the following patents: WO/2025/229604 and WO/2025/229601.