Multiphysics Energy Research Center
University of Missouri

14th IEA HEAT PUMP CONFERENCE

Experimental Study of Steam-Driven Ejector Heat Pump

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Introduction

- In the United States an estimated 18% of residential energy consumption is used for domestic hot water (DHW) production.
- Significant amount of the power used to power these systems is lost in the form of waste heat.
- A 2015 study by Lawrence Livermore National Laboratory estimated waste heat accounted for 60% of total US energy consumption.
- Thermally driven driven heat pumps can be used to increase the efficiency of these systems by being able to recycle the waste heat back into the system.
- Ejector heat pumps (EHP) can utilize recycled thermal energy and require little maintenance, however, have be found to be limited by their low efficiencies and narrow operating range when utilizing a single working fluid.
- Ejector studies have traditionally been done with the ejector operating in the critical zone, however, it has been shown that higher backpressures and temperature lifts can be reached if the ejector is operated in subcritical conditions.
- The goal of this investigation is focused on the ejector cycle to try and achieve the maximum condensing temperature possible, in order to develop the single-stage gas-fired ejector heat pump water heater which aims to produce a domestic hot water (DHW) supply 14.5 °C to a target delivery temperature of 51.7 °C.

How an EHP works

Pressure lift ratios

Primary nozzle:

$$\frac{P_{o,p}}{P_{NXP}} = \left[1 - \frac{1}{\eta_p} + \frac{1}{\eta_p\left(1 + \frac{k_{PF}-1}{2} M_{1,PF}^2\right)}\right]^{\frac{k_{PF}}{k_{PF}-1}}$$

Normal shock:

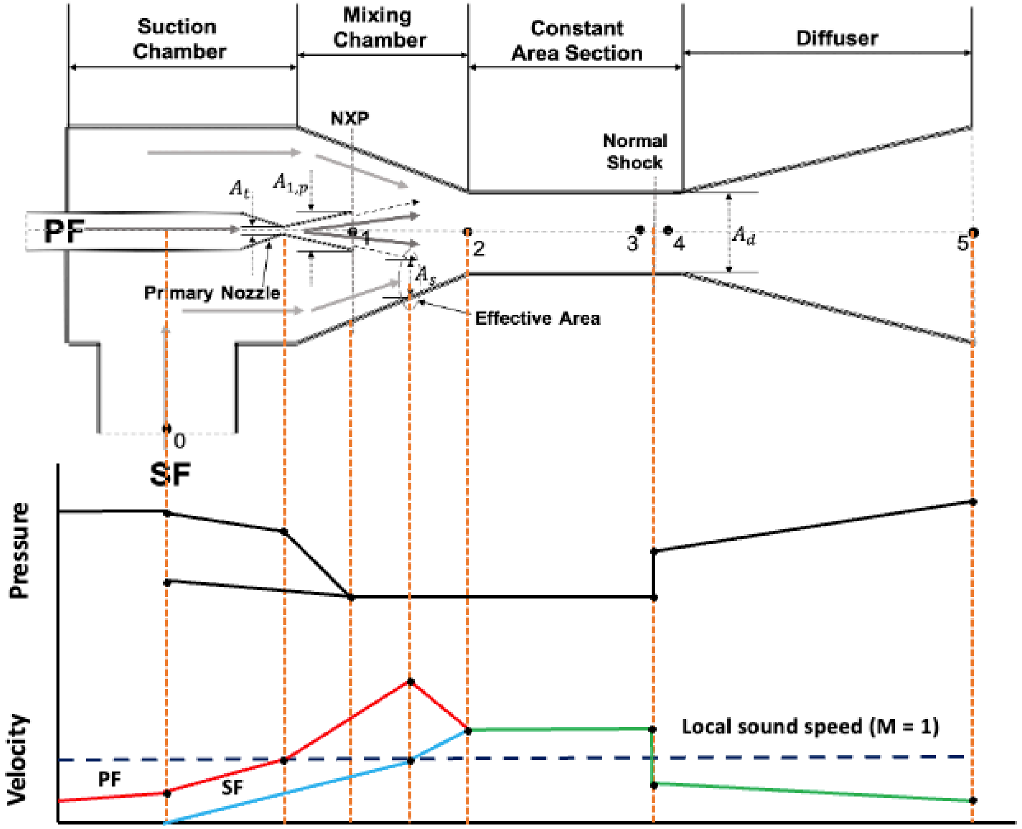
$$\frac{P_{4,mix}}{P_{3,mix}} = \frac{1 + k_{mix} M_{3,mix}^2}{1 + k_{mix} M_{4,mix}^2}$$

Diffuser:

$$\frac{P_b}{P_{4,mix}} = \left[\frac{\eta_d (k_{mix}-1)}{2} M_{4,mix}^2 + 1\right]^{\frac{k_{mix}}{k_{mix}-1}}$$

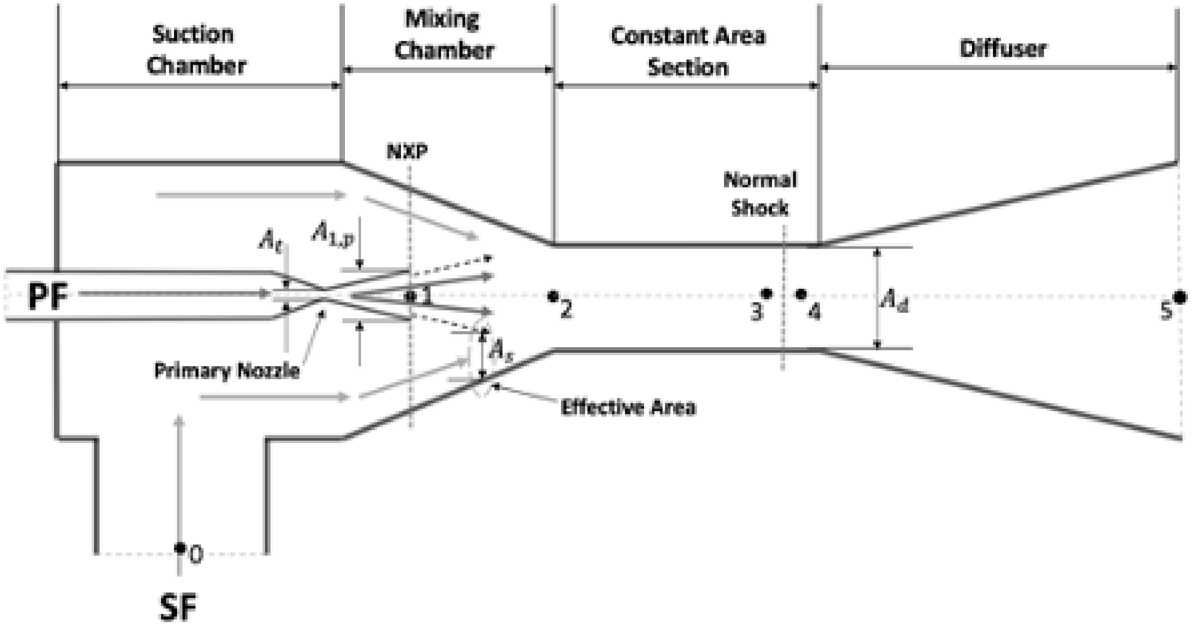
Ejector performance

$$COP_{EJT} = \frac{Q_s}{Q_p} = \frac{\dot{m}_s h_{lv,s}}{\dot{m}_p h_{lv,p}} = \omega \frac{h_{lv,s}}{h_{lv,p}}$$

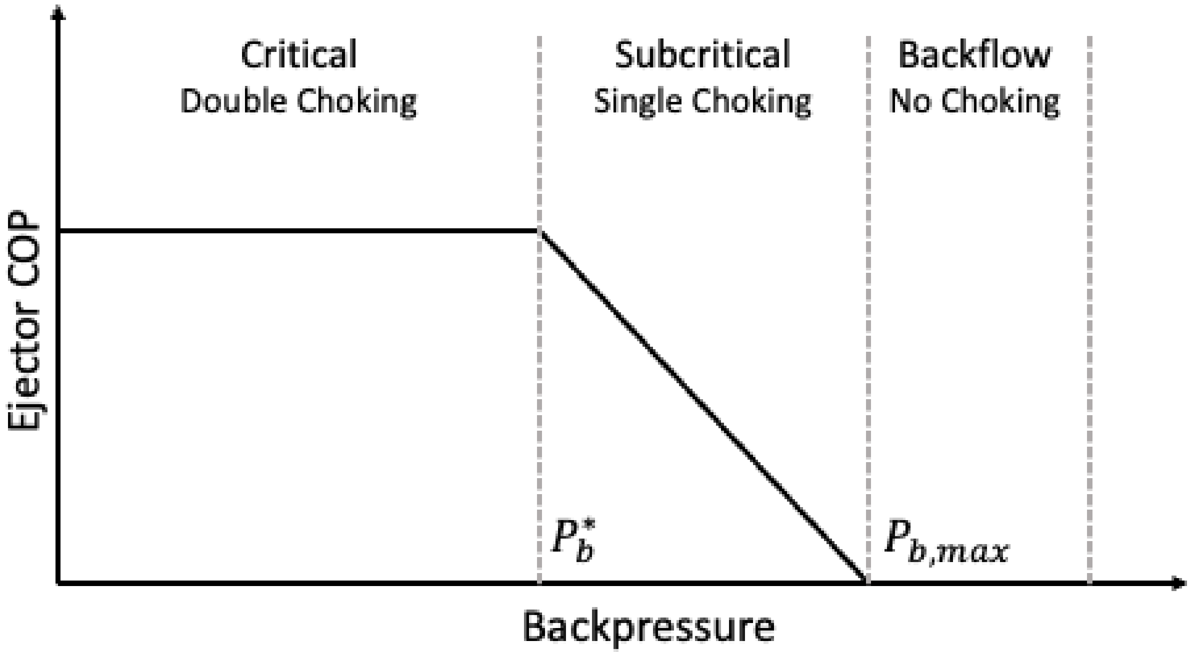


Pressure and velocity profiles of fluid flow along an ejector

Subcritical Conditions



Schematic of ejector



Effect of backpressure on the COP of an ejector

Experimental Setup

High Temperature Evaporator (HTE):

$$\dot{Q}_{HTE} = I \times V$$

Low Temperature Evaporator (HTE):

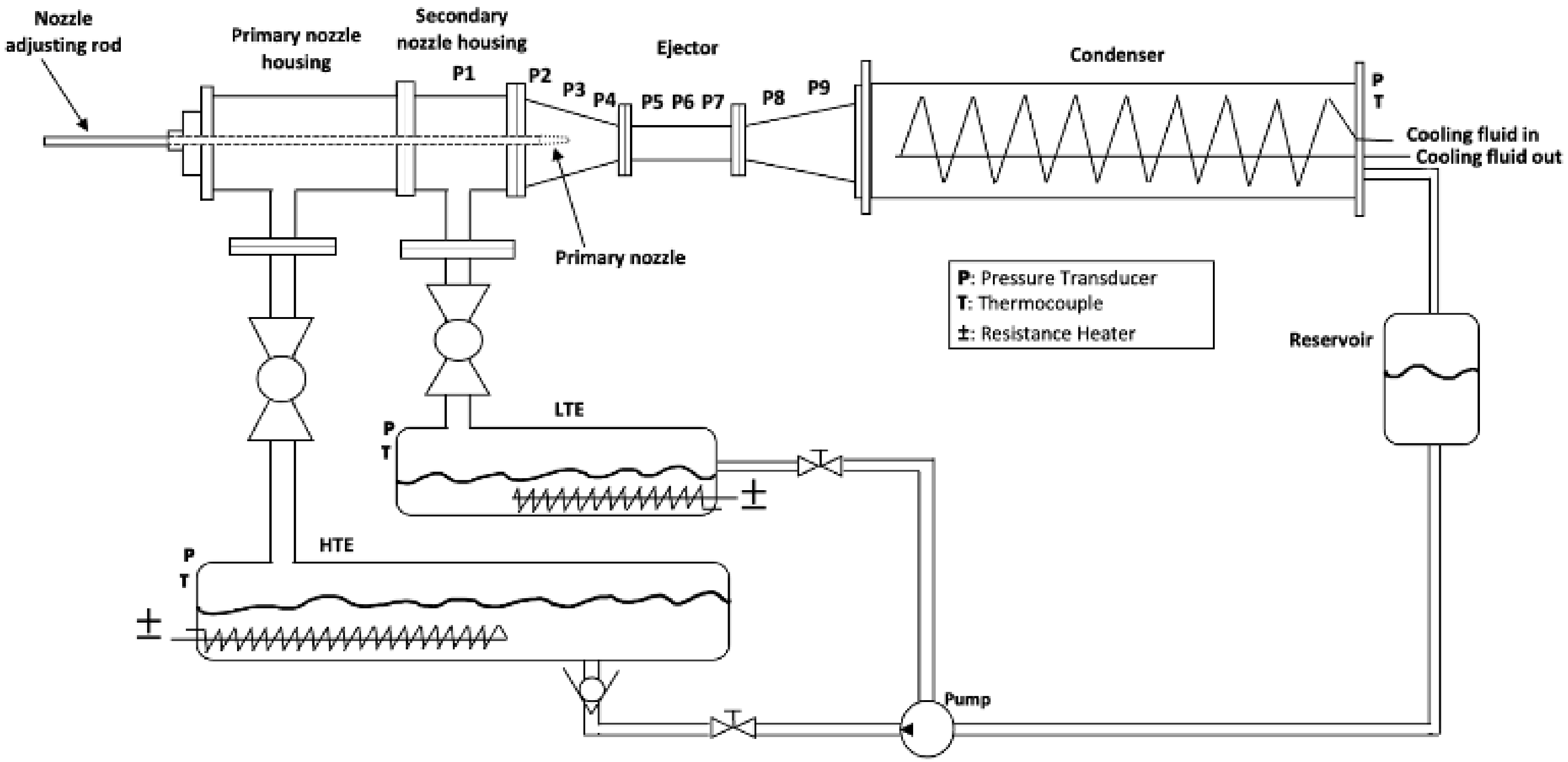
$$\dot{Q}_{LTE} = I \times V$$

Condenser (Cond):

$$\dot{Q}_{cond} = \dot{m}_w c_p (T_{cool,out} - T_{cool,in})$$

EHP Performance:

$$COP_{EHP} = \frac{\dot{Q}_{cond}}{\dot{Q}_{HTE}}$$



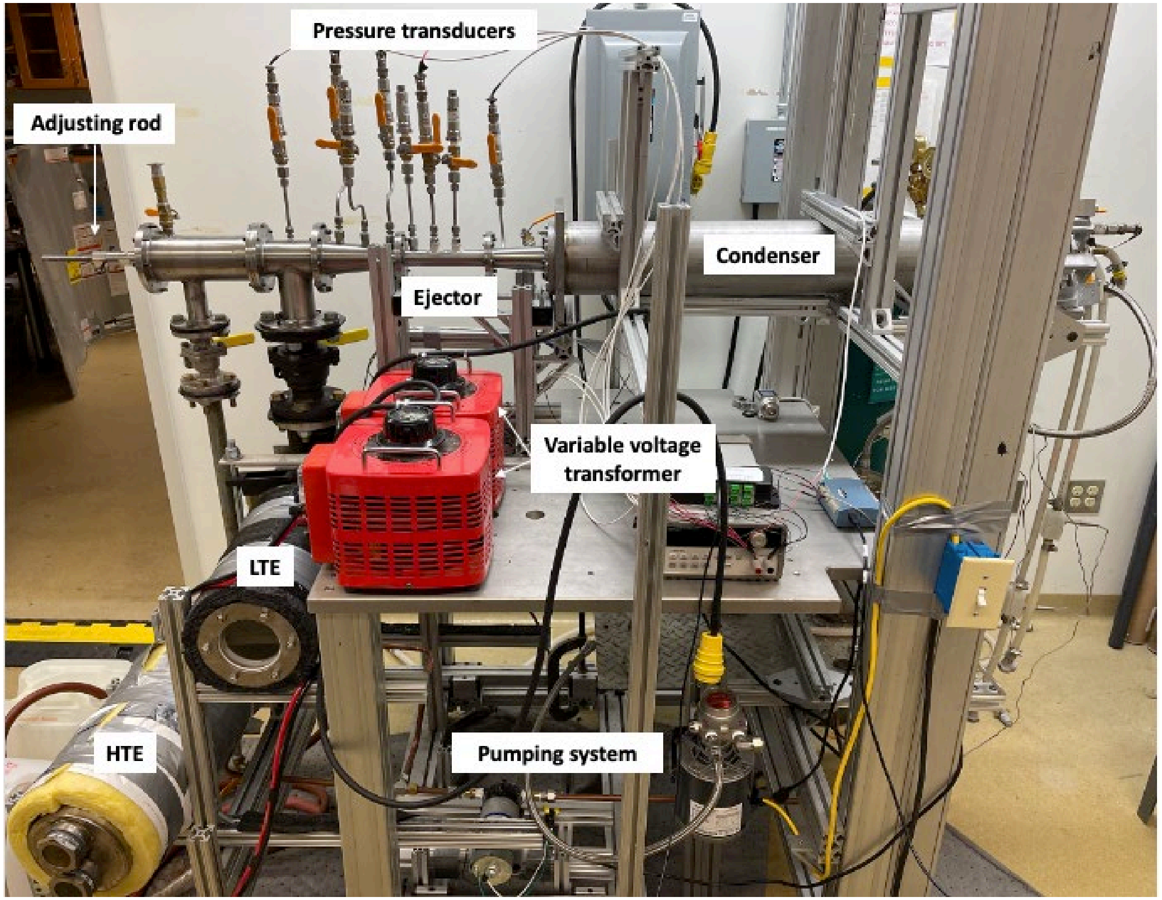
Experimental Input Conditions

Two primary nozzles were tested:

- Primary Nozzle 1:
  - Throat diameter = 1.5 mm, Area Ratio = 36
- Primary Nozzle 2:
  - Throat diameter = 2.0 mm, Area Ratio = 36

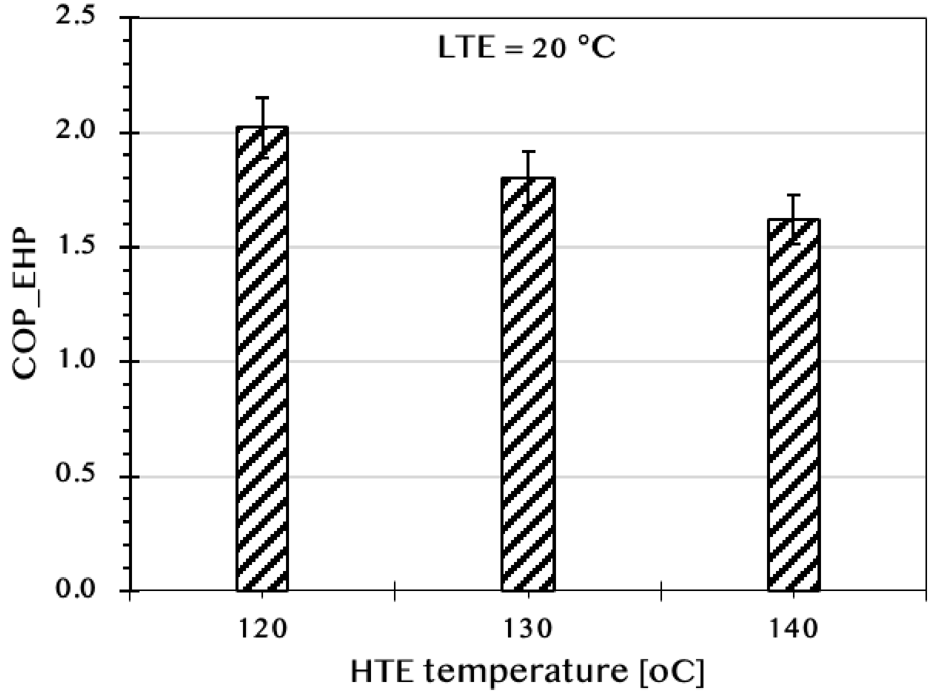
Input conditions:

- $T_{HTE} = 120, 130, \& \ 140\ °C$
- $T_{LTE} = 10, 15, \& \ 20\ °C$
  - Additional trials were run at T_{LTE} = 25 and 30 °C for Primary Nozzle 1
- Mass flow rate of cooling water ($\dot{m}_w$) = 1.7 GPM
- $T_{cool,in}$ = 14.5 °C

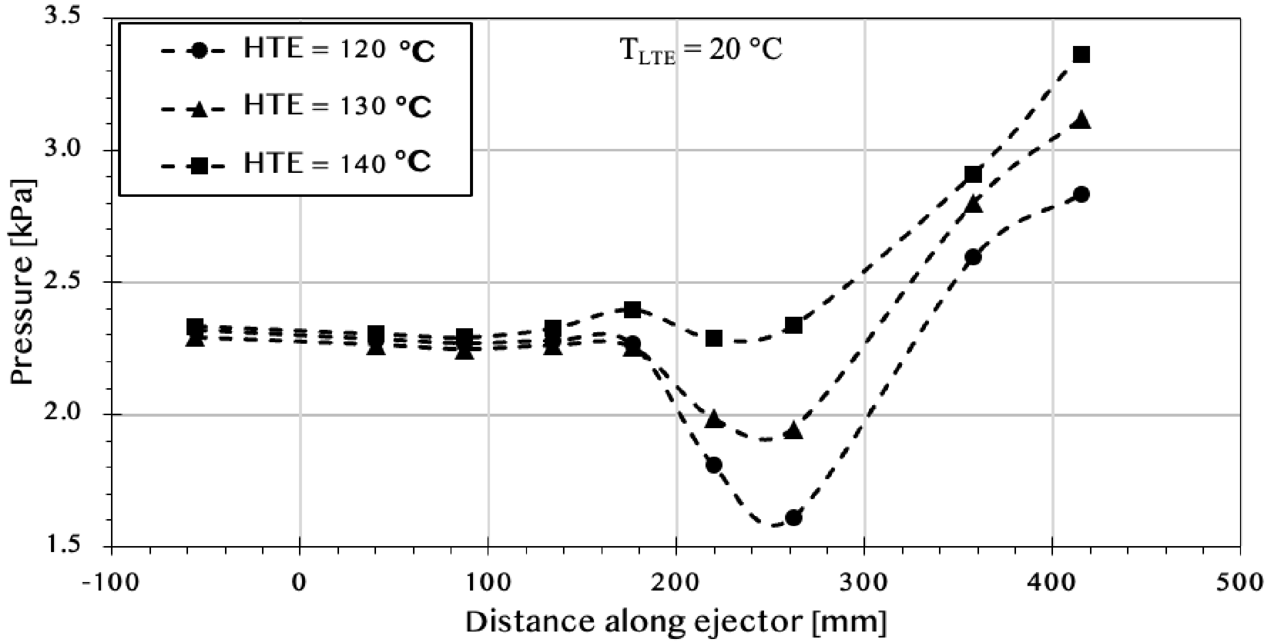


HTE Temperature Effect

- Increasing the HTE temperature led to lower COP_{EHP} values but higher backpressures
- From $T_{HTE} = 120\ °C$ to 140 °C, the COP_{EHP} decreased 20%, 2.02 to 1.62, but the corresponding backpressures were 2.8 and 3.4 kPa (22.88 and 26.12 °C)
- Pressure drop at 220 mm occurred due to increase in the velocity of the fluid flow.
- Normal shock occurred between 260 and 360 mm leading to sharp rise in static pressure and decrease in fluid flow



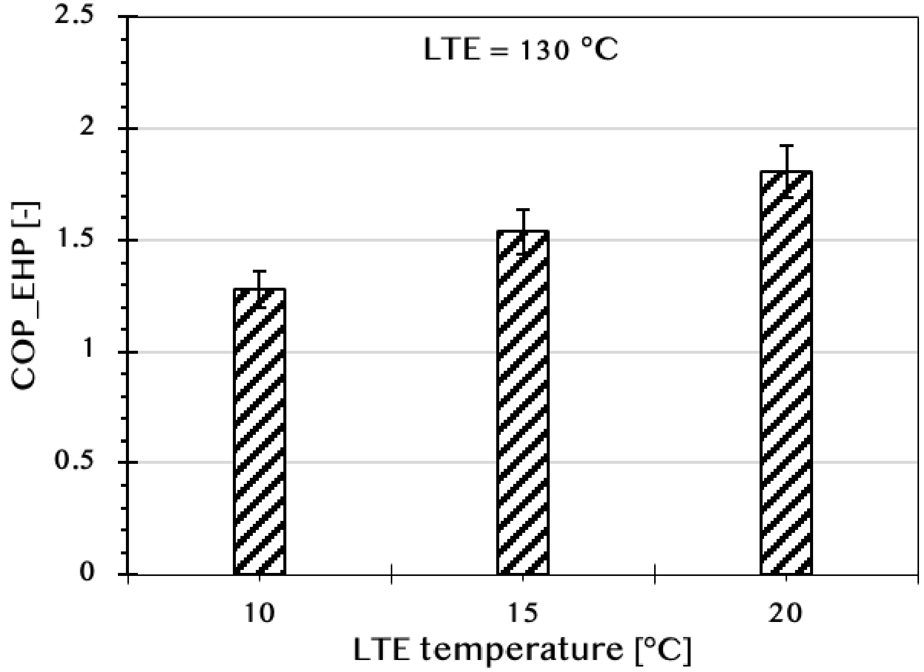
HTE temperature effect on the EHP COP using a nozzle throat diameter of 1.5 mm



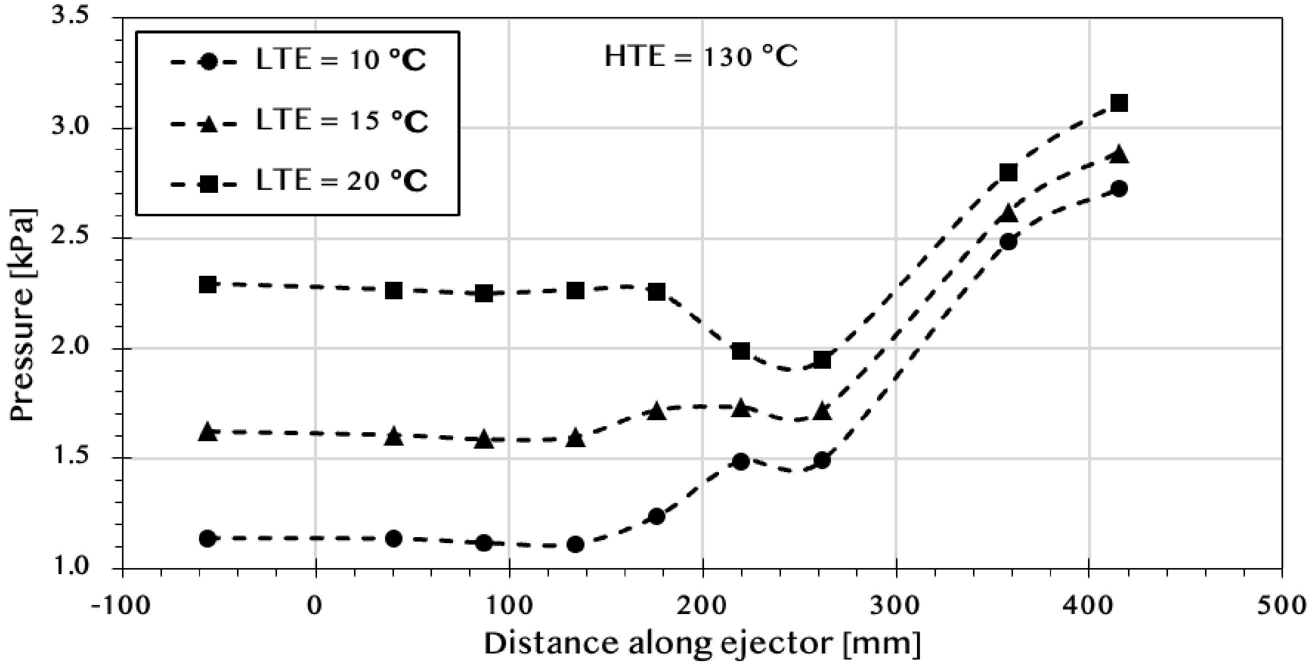
Pressure profile along the ejector at various HTE temperatures for nozzle throat diameter of 1.5 mm.

LTE Temperature Effect

- Increasing the LTE temperature led to higher COP_{EHP} values and back pressures
- From $T_{LTE} = 10\ °C$ to 20 °C, the COP_{EHP} increased 40%, 1.28 to 1.62
- For lower LTE temperatures, less water vapor is entrained into the mixing chamber and that entrained vapor has less momentum



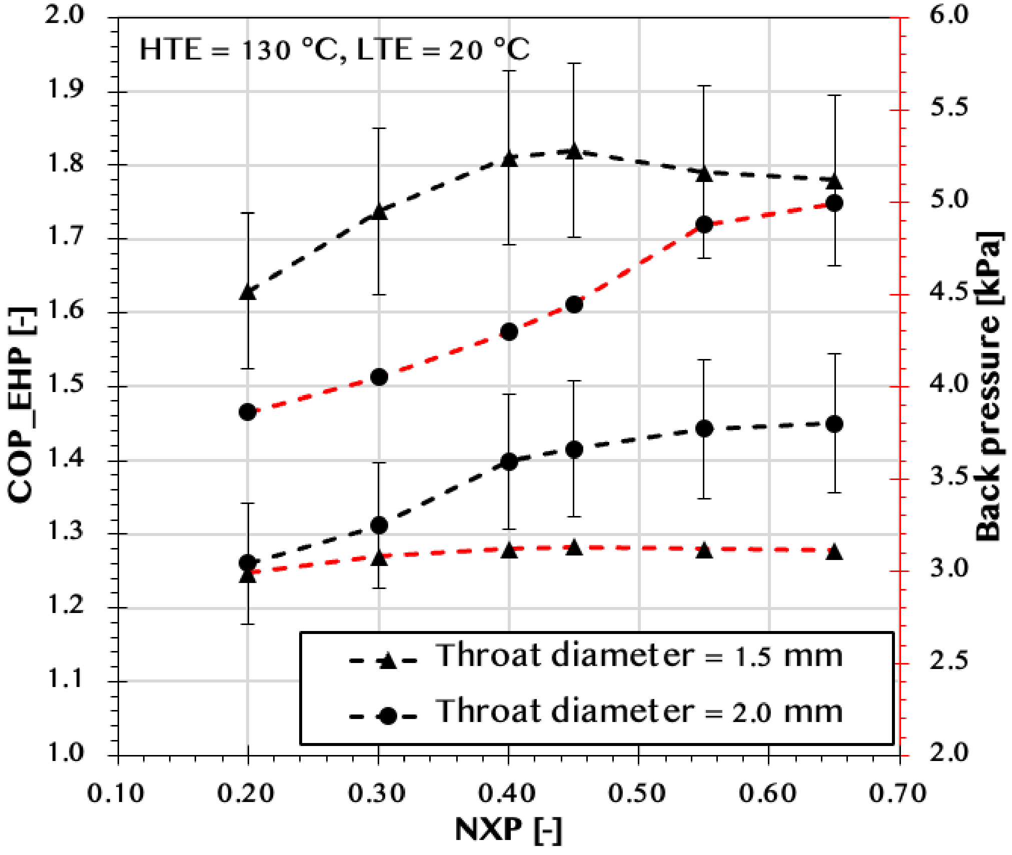
LTE temperature effect on the EHP COP using a nozzle throat diameter of 1.5 mm



Pressure profile along the ejector at various LTE temperatures for nozzle throat diameter of 1.5 mm.

Effect of Nozzle Throat Diameter

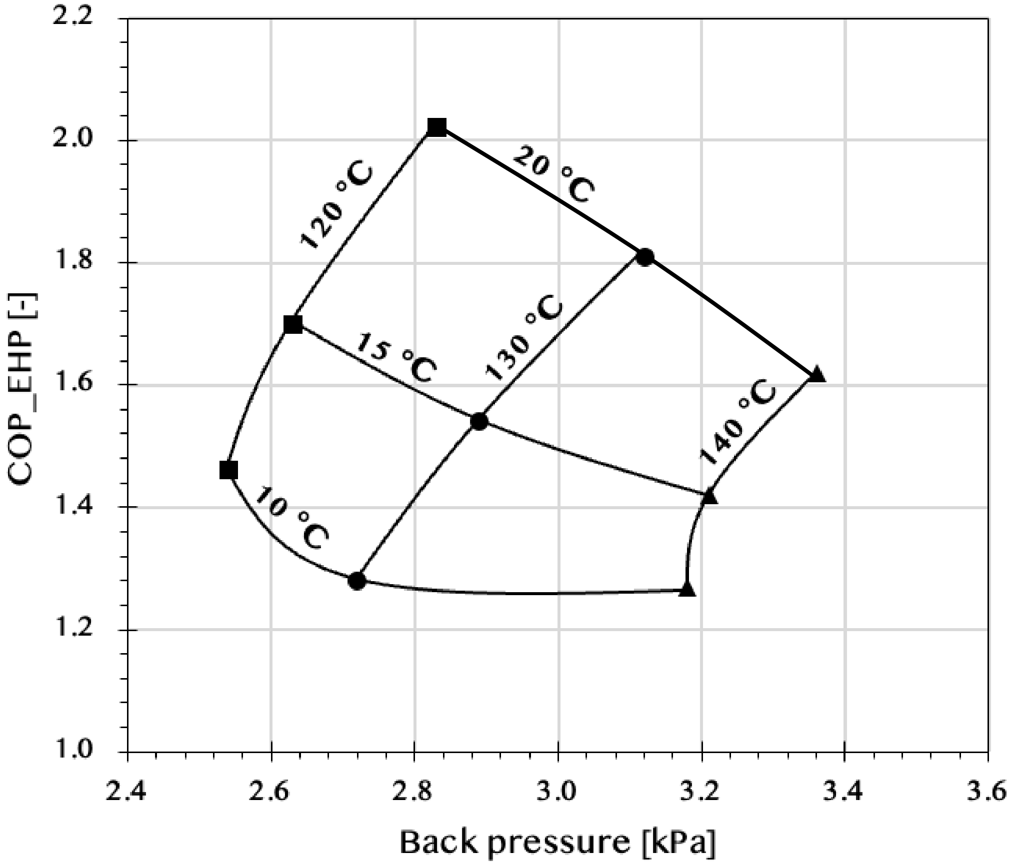
- The primary nozzle with a throat diameter of 1.5 mm was found to perform better than that with the 2.0 mm throat.
- A decrease in the throat diameter results in a low PF mass flow rate travelling through the nozzle.
- This is directly related to the heat input into the HTE, leading to a significant increase in COP_{EHP}
- For a NXP = 0.40 a 29% in COP_{EHP} was observed when decreasing the nozzle throat diameter (1.40 to 1.80)
- Smaller throat diameter = higher COP_{EHP}
- Larger throat diameter = higher backpressures
- Results emphasize importance of optimizing geometry of the primary nozzle to find the best compromise between the two.



EHP COP and back pressure using two different throat diameters at various NXPs

Ejector Performance

- Performance map which can be used to select ideal working conditions to suit the requirements of the EHP system
- Higher LTE temperatures – higher COP_{EHP} and backpressures
- Higher HTE temperatures – lower COP_{EHP} and higher backpressures



Performance map of EHP using a 1.5 mm nozzle at NXP of 0.40.

Conclusions

- A steam-driven ejector heat pump for water heating purposes was built and tested to determine the effects of the operating conditions and design parameters of the COP_{EHP} and backpressure under sub-critical conditions
- Nine pressure transducers were installed along the axis of the ejector to observe the effects the operating conditions had on the static pressure profile of the steam as it travels through the ejector.
- The experimental results indicate larger LTE temperatures are better for larger COP_{EHP} and backpressures or a larger temperature lift for the EHP, while larger HTE temperatures also lead to higher backpressures, but the COP_{EHP} is compromised.
- larger throat diameter resulted in lower COP_{EHP} and larger backpressures, indicating the importance of designing a primary nozzle to get the desired trade-off between the COP_{EHP} and backpressure.
- An ejector performance map is provided to help select the operating conditions for the desired set point for the EHP system
- From this investigation it can be concluded that further work needs to be done to further develop a clear understanding of the behaviour of the fluid flow through an ejector, which can then be used to further improve the EHP system.

Thank you

Questions?

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