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Review

Two-Phase Volumetric Expanders: A Review of the State-of-the-Art

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Abstract: Two-phase expansion is the process where a fluid undergoes a pressure drop through or in the liquid–vapor dome. This operation was historically avoided. However, currently it is studied for a multitude of processes. Due to the volume increase in volumetric expanders, a pressure drop occurs in the fluid resulting in flashing phenomena occurring. These phenomena have been studied before in other processes such as two-phase flows or static flash. However, this has not been extensively studied in volumetric expanders and is mostly neglected. Even if data has shown this is not always neglectable depending on the expander type. The thermal non-equilibrium occurring can be modeled on different principles of flashing flows, such as the mixture model, boiling delay model, and homogeneous relaxation model. The main application area in current literature for volumetric two-phase expansion machines, is in low-temperature two-phase heat-to-power cycles. These cycles have shown benefit over classic options if expanders are available with efficiencies in the range of at least 75%. Experimental investigation of expanders in two-phase operation, though lacking in quantity, has shown that this is an achievable goal. However, the know-how to accomplish this requires more studies, both experimentally and in modeling techniques for the different phenomena occurring within these expanders. The present work provides a brief but comprehensive overview of the available experimental data, applicable flashing modeling techniques, and available models of volumetric two-phase expanders.

Keywords: two-phase; volumetric expander; review

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1. Introduction

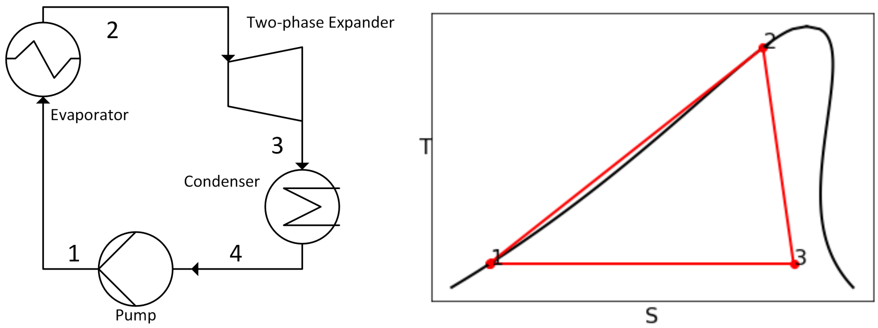
Expansion processes generating work from two-phase liquid–vapor flows are typically avoided. Common issues ranged from condensation in steam engines [1] to liquid impact erosion in turbomachinery [2]. Yet, this review handles exactly the particular topic of utilizing two-phase fluid expansion, its possibilities, and the current status of experimental knowledge.

1.1. Two-Phase Expander Applications

Applications for two-phase expanders are where a single working fluid two-phase liquid–vapor mixture undergoes a pressure drop. Such as in liquid injection cycles [3] or instead of a throttling valve in a heat pump cycle [4–6]. This throttling valve could also be substituted by a two-phase ejector, which will not be included within this review as it was elaborately discussed by [7,8].

Another important application of two-phase expanders is found in the scope of low-grade heat-to-power conversion. These low-grade heat sources range from geothermal or solar heat to the residual heat of industrial processes. The recuperation of low-grade heat-to-power is commercially available technology through the use of the Organic Rankine Cycle (ORC). The ORC can be a basic Rankine cycle or one of the many variations with, for example, multiple pressure levels, the addition of a recuperator or, among others, can include two-phase expansion. Ref. [9] recommends the investigation of two-phase expanders to increase the performance of heat-to-power cycles. However, this technology is not commercially available. Based on the modeling work of [10,11] the authors concluded that optimized two-phase operation of expanders can improve the system power by nearly 50% in specific operating conditions.

An ORC with two-phase expansion occurs when saturated liquid enters the expander of the ORC architecture, the cycle is called a trilateral cycle (TLC) or a trilateral flash cycle (TFC). The inlet state of the expander can also be in the two-phase region. If this is the case, then the cycle is referred to as a partial evaporation organic Rankine cycle (PEORC) or a wet organic Rankine cycle (WORC). A schematic diagram and a temperature-entropy diagram of the TLC are represented in Figure 1. It consists of four parts: a condenser, an evaporator, a pump, and an expander. The difference with a basic ORC is that the evaporator no longer evaporates the working fluid in the TLC. Instead, the fluid entering the expander is in a saturated liquid state and during the expansion process, the fluid is in the two-phase region as can be seen by point 3 on the T-s diagram in Figure 1b. There is thus a need for an efficient expander capable of two-phase expansion. The heat exchanger that adds heat to the working fluid no longer evaporates the fluid, yet it is still referred to as the evaporator in literature.



(**a**) (**b**)

Figure 1. Trilateral Cycle (TLC) [12]. (**a**) Schematic diagram (**b**) T-s diagram.

It was concluded by [13] that two-phase expansion devices should have an isentropic efficiency of at least 75% to be interesting for power generation applications, which is a realistic design goal. The main difficulty is the lack of practical and efficient two-phase expanders capable of receiving a liquid or a single working fluid two-phase liquid–vapor mixture and the absence of the methods to design these.

Ref. [12] showed that the TLC obtains a larger net power output, thermal efficiency, and exergy efficiency compared to the basic ORC with an increase of 37%. Yet, for evaporation temperatures greater than 135 °C the TLC does perform worse from a financial aspect due to the extra requirements of the heat exchangers, although it does perform better thermodynamically. Ref. [14] also compared the exergy efficiency of power production of the TLC with the ORC. This was defined by the authors as the ratio of the produced power to the incoming exergy flow of the heat carrier which is also referred to as the second law efficiency. They conclude that the exergy efficiency of power production for the TLC is between 14% to 29% higher than the ORC. Yet, because the authors used water as the working fluid, the volume flow rate of the TLC was higher compared to the ORC by a factor of 2.8 or more. This is expected to drop when the working fluid is changed to current refrigerants. The TLC has been practically tested with a small-scale power plant [15] which resulted in 20–40% more power production compared to a conventional ORC. This power plant applied the VPT turbine mentioned before.

As mentioned earlier, another option is to partially evaporate the working fluid up to an optimal vapor quality. This was investigated by [16] where the PEORC was compared to the TLC. The authors also compared the PEORC to the subcritical ORC and the transcritical ORC [17]. The authors show that the PEORC can improve the net power output in comparison to the TLC and that it has a greater second law efficiency than both the subcritical and transcritical ORCs.

1.2. Principles of Flashing

During expansion of a two-phase fluid, flashing will occur. Flashing [18,19] is a physical phenomenon in liquids. It represents a change from liquid to vapor as a result of a sudden decrease in the pressure below the saturation pressure. The heat cannot be contained in the liquid as sensible heat and a metastable superheated liquid occurs [20]. A rapid transfer of heat and mass occurs while the fluid returns to a stable thermodynamic state [21]. This metastable liquid also has a maximum value. This limit is known as the spinodal curve which separates the metastable region from the unstable region in equations of state (EOS) [22,23]. The process of flashing is found and studied in many places such as static flash, boiling liquid expanding vapor explosions (BLEVE) and safety valves, flashing jets, pressurized water reactors, and many more [24–26]. However, the phenomena known through these areas of study have not been directly applied to the case of volumetric two-phase expanders. That is where this review will focus hereafter.

1.3. Expander Types

When considering what type of expander is best suited for an application in single-phase operation, the similarity parameters, specific speed, and specific diameter are often used as defined, respectively, in Equations (1) and (2).

$$N_s = N \cdot \sqrt{\frac{\dot{V}}{(\Delta h)^{3/2}}} \tag{1}$$

$$D_s = \frac{D \cdot (\Delta h)^{1/4}}{\sqrt{\dot{V}}} \tag{2}$$

where N is the rotational speed of the expansion machine, $\dot{V}$ is the volumetric flow rate, D is the characteristic diameter and Δh is the enthalpy difference across the machine. These two numbers can be calculated readily from the design requirements and, by presenting the different types of expansion machines on the same diagram, the most feasible turbine type can be chosen [27]. Balje diagrams can be created for every expander type [28,29] and later employed in design.

Yet, in the event where two-phase fluid is expected, it is not as straightforward to choose turbomachine expanders because the blades could be at risk of impact erosion. However, a plethora of applications where two-phase expansion can be used is suited well to volumetric machines.

1.4. Volumetric Expander Types for Two-Phase Expansion

Volumetric expanders are preferred for the low-temperature heat-to-power application as they have low rotational speeds with low flow rates.This matches well with the current requirements of ORCs. Furthermore, they can cope with relatively high-pressure ratios compared to single-stage turbo expanders and can also inherently handle liquid–vapor mixtures. Both of these traits are beneficial to the TLC and PEORC.

Each type of volumetric expander has some benefits and drawbacks, these are discussed by [30,31]. Currently, only two types are primarily considered for the use of two-phase expanders. These are the screw or Lysholm expander and the piston or reciprocating expander. The most promising type for two-phase expansion is the Lysolm expander. The main benefit of this type is that both phases can be considered to be mixed well. Giving acceptable results when thermodynamic equilibrium is assumed [32–34]. This implies that a simple homogeneous mixture model in thermodynamic equilibrium could be considered. The different modeling approaches for the fluid state are further discussed in Section 2.

Other types of screw expanders, such as the single screw, were deemed too mechanically complex [35]. However, even these are appearing as a possible alternative [36,37].

The reciprocating expander is interesting for applications with higher pressure ratios and lower velocities. The main benefit of this expander type is the built-in volume ratio (BVR). The reciprocating expander is the type that has the largest BVR of all volumetric expander types. This trait is in accordance with the requirements for two-phase expanders which require large volume ratios to accompany the flashing process. A drawback of using this type of expander is the modeling of the expansion process. Assuming thermodynamic equilibrium does not give acceptable results with actual experimental results [38] as it did for Lysholm expanders. It requires a better understanding of the flashing process taking place during expansion.

In volumetric expanders, this sudden depressurization is a result of the increasing working volume. Due to the shape of a reciprocating expander, the flashing process could be compared to static flash experiments [19]. Static flash stands for the case where the fluid remains static in the horizontal direction during the flashing process [39]. These processes have been researched before. For example, as occurring in the desalination process [40] of drinking water production from seawater or as a process taking place in safety valves [41]. The phenomena and data found in literature about static flashing could [20] prove to also be useful in describing the phenomena taking place in volumetric expanders, and most notably reciprocating expanders. To the author's knowledge, other volumetric expander types, such as scroll and vane expanders, have not been found in two-phase expansion research.

1.5. Positioning of This Review

Implementing two-phase expansion technology requires methods to accurately predict the expansion process in various thermodynamic cycles and expander types. Only with this fundamental data, efficient two-phase expanders can be designed. In the following, the review will first shortly describe the possible techniques to model the working fluids' thermodynamic state during the expansion process. Afterward, a summary of the available experimental data is given. Lastly, the specific models applicable to a volumetric expander are also detailed. The gaps in current literature are highlighted and recommendations for future work are given.

2. Methods for Modeling Two-Phase Expansion

There is a multitude of modeling techniques and codes developed for the simulation of flashing. They are often subdivided based on the made assumptions. The assumptions that can be made are that the phases are in thermal equilibrium and/or that they are in mechanical equilibrium. In the context of volumetric expanders, the mechanical equilibrium is assumed as both phases occupy the same expansion chamber or chambers. If thermal equilibrium is assumed as well, then the homogeneous equilibrium model (HEM) can be applied, in the other case, the homogeneous relaxation model (HRM), boiling delay model, or mixture model is used. These techniques will be elaborated upon in the following sections. For other modeling techniques where mechanical equilibrium is not assumed (i.e., in continuous flows), the authors refer to [26] for a review on flashing flow modeling.

2.1. Homogeneous Equilibrium Model

As stated previously, in the homogeneous equilibrium model it is assumed that there is thermal equilibrium between the phases. This implies that both phases share the same saturation temperature:

$$T_g = T_l \tag{3}$$

In which the subscript g stands for the vapor or gas phase and the subscript l for the liquid phase. From this, it follows that the two-phase mixture behaves such as a pseudo single-phase in which the thermodynamic properties can be expressed commonly as in Equation (4). In which x is the mass based vapor quality and y can be any fluid property [26].

$$y = x \cdot y_g + (1 - x) \cdot y_l \tag{4}$$

The HEM consists of three equations: the mass, momentum, and energy conservation equations [42] where the fluid is modeled as a homogeneous mixture of gas and liquid.

Due to its simplicity, it was often used in the past and chosen as the basis for many system codes. However, this approach induces large errors when the equilibrium assumptions do not apply, such as processes in very small time intervals. This is, for example, the case for the reciprocating expander. Even though the expansion process in screw expanders has a similar time constant compared to reciprocating expanders, the HEM can still be used to describe this type of volumetric expander as was shown by [43]. It is speculated that this approach is valid due to the better mixing of the phases within the chambers of a screw expander in comparison to reciprocating ones. Ref. [34] modeled a screw expander with liquid injection as well. The authors also found that assuming thermal equilibrium gives good results compared to the experiments. Ref. [44] used the HEM assumptions within a commercial software environment to model the screw expander within a TLC cycle. This model was studied by [45], in which the authors concluded that the intake phenomena have a large impact on the overall performance of the machine. The constructed model showed that isentropic efficiencies can go up to 83.1%, depending on the operation conditions.

Lastly, comprehensive research on screw expander TLC is found in the works of [33,46]. Due to developments in screw expander technology, they conclusively showed that with the right choice of working fluid a two-phase screw expander can be constructed for use in a TFC. However, water is not found a suitable working fluid within this type of cycle. The net output from the cycle is 10 to 80% greater when compared to a basic ORC. The machines retain a similar size as well.

2.2. Mixture Model

This methodology solves the continuity equations for both the phases and the mixture. The vapor generation rate is postulated to arise from interphase heat transfer. One equation that is often applied to calculate the vapor generation rate is the interfacial exchange model. Given in Equation (5).

$$\mathcal{T} = A_i \cdot \frac{\dot{q}}{h_{gl}} \tag{5}$$

wherein $\mathcal{T}$ is the vapor generation rate, A_i the interfacial area, $\dot{q}$ the total heat flux, from both phases, transferring to the phase interface and h_{gl} is the latent heat of vaporization.

This model is accurate but, depending on the complexity, requires several closure equations. Constitutive equations for the determination of friction force and nucleation rate can be implemented. This model was applied by [38,47], which was evaluated with their previously mentioned experiments [48,49]. The authors considered that the vaporization was mainly driven due to the heat transfer from the liquid to the phase change interface. The model is capable of predicting their data, both the pressure drop and adiabatic efficiency are within an accuracy window of about 5% and this considering both with and without charge and discharge processes. The adiabatic efficiencies are predicted to reach 84%.

2.3. Boiling Delay Model

The boiling delay model states that the boiling only happens when a certain degree of superheat in the liquid is reached. Then the nucleation of bubbles starts to take place. This liquid superheat implies that there is no thermal equilibrium assumption. The bubble nucleation and growth also limits the eventual vapor generation rate. There is a need for two-phase mixture conservation equations beyond the flashing inception, including property calculations for the metastable liquid thermodynamic properties. This modeling technique could be used in the future for very detailed reciprocating expander models. However, due to the need for sufficiently accurate analytical expressions for bubble nucleation and growth rate, there are currently no examples of its use in volumetric expanders. However, Ref. [50] did apply droplet modeling in the stator nozzles of the wet-to-dry cycle, taking into account both thermal and mechanical non-equilibrium. As explained before, this cycle avoids erosion on the blades by only having liquid in the nozzles and superheated vapor in the rotor. This can be easily modeled in equilibrium but [50] showed that this is also feasible when taking non-equilibrium into account.

2.4. Homogeneous Relaxation Model

The homogeneous relaxation model (HRM) is similar to the HEM in the sense that it makes use of the same three continuity equations. However, there is no thermal equilibrium assumption. Instead, the following equation is added [42] which is the vapor mass balance equation.

$$\frac{\partial x}{\partial t} + w\frac{\partial w}{\partial z} = \frac{\mathcal{T}}{\rho} \tag{6}$$

Herein, $\mathcal{T}$ represents the vapor generation rate and x is the actual vapor quality. An implication of not assuming thermal equilibrium is that the liquid and vapor phase temperatures are different, this implies that the total state cannot be represented by Equation (4) as the liquid is in a superheated state. The thermodynamic properties are instead defined as in Equation (7) [42].

$$y = x \cdot y_{s,g} + (1 - x) \cdot y_{m,l} \tag{7}$$

In which the subscripts s and g stand for saturated vapor which is only dependent on the saturation pressure, the subscripts m and l stand for metastable liquid which is dependent on both the pressure and the liquid temperature. From the previous, it thus follows that the fluid is assumed to be a mixture of saturated vapor and superheated liquid, both on the same pressure. Ref. [42] adopted the relaxation equation to the simplest linear approximation, as was successfully performed in the past by other researchers. This results in the following equation.

$$\frac{Dx}{Dt} = \frac{\mathcal{T}}{\rho} = -\frac{x - \bar{x}}{\theta} \tag{8}$$

Herein, x is the actual vapor quality and $\bar{x}$ is the unconstrained equilibrium value of the vapor quality. θ is the local relaxation time and represents the time needed for the fluid to reach equilibrium, for which a relation is constructed. Lastly, Ref. [42] also presented correlations for θ but they were only verified for water with the Moby-Dick experiments. The first correlation gives comparatively good results for small pressures, up to 10 bar.

$$\theta = \theta_0 \cdot \epsilon^{-0.257} \cdot \psi^{-2.24} \tag{9}$$

$$\epsilon = \frac{x \cdot \mu_{s,g}}{\mu} \tag{10}$$

$$\psi = \frac{P_s(T_{in}) - P}{P_s(T_{in})} \tag{11}$$

where θ_0 is equal to 6.51×10^{-4} s. For higher pressures, greater than 10 bar, Equation (9) is substituted for Equation (12).

$$\theta = \theta_0 \cdot \epsilon^{-0.54} \cdot \phi^{-1.76} \tag{12}$$

$$\phi = \frac{P_s(T_{in}) - P}{P_c - P_s(T_{in})} \tag{13}$$

In Equation (12), θ_0 is equal to 3.84×10^{-7} s. P_c is the pressure at the critical point. These equations were tested by [51] and they concluded that this rather simple equation, which only describes one possible mechanism for mass exchange between the phases, can still represent complicated processes. The authors do note that the flashing rate is very sensitive to the value of θ.

Ref. [52] also defined an expression for the relaxation time. Instead of using dimensional analysis and construction of a correlation out of experimental data, the authors evaluated the relaxation time theoretically based on the heat flux around vapor bubbles in the superheated liquid. The authors notice that an increase in the initial void fraction corresponds to a decrease in the relaxation time θ and that the relaxation time decreases for higher values of liquid superheat.

As mentioned before, the HRM model was found to be suited for reciprocating expanders while the HEM can be used for describing the expansion process in screw expanders. This observation is also made in the work of [53]. The authors evaluated the thermodynamic disequilibrium loss, of which the effects increase when the rotation speed increases or if the injection temperature decreases. In these scenarios, with high expander speeds and low heat source temperatures, the authors consider the screw expander to be more suitable. In [54], the authors develop a model for estimating these losses. This model is based on the intake ratio, as the temperature difference between the liquid and vapor phases mainly appears at the initial stage of the two-phase expansion process.

The HRM model has also not yet been fully implemented in an expander model, but [55] has started with the design of a reciprocating expander test-rig. The goal hereby is to gain a better understanding of the flashing principles during variable volume flashing. The model which is being created is based on the HRM model. Initially [56] the model did not yet include an equation for the relaxation variable, instead it was assumed that the evaporation happens instantly. In subsequent work, Ref. [57] the HRM model was included in the reciprocating expander model, but without fitting of the experimental parameters as there is no data available.

A similar method is known as the Delayed Equilibrium Model (DEM) [58] which works on the same principles but uses a three-phase mixture instead of a two-phase mixture. The three phases are saturated vapor, saturated liquid, and superheated liquid states.

2.5. Conclusions and Comparison

Many models have been constructed and used in literature to describe two-phase phenomena. These are mostly applied to flows and other continuous processes and can be subdivided based on taken assumptions. For the specific use of describing the flashing process in a volumetric expander, the possibilities are limited. Because, up until now, the working fluid is assumed to be in mechanical equilibrium, imposing an equilibrium pressure in the two phases, similar to the flashing process where thermal non-equilibrium is used to characterize the system. The most used technique assumes complete equilibrium due to its simplicity and ease of implementation in software. It was shown that this methodology suffices to describe the Lysholm expander, this is speculated to be due to the good mixing within this type of expander. When thermal non-equilibrium is assumed, three methodologies are possible. The mixture model, which solves a given set of continuity equations, was applied by [47] after the authors measured a superheated liquid. The authors were able to predict their experiments by the implementation of the interfacial heat and mass transfer model. Secondly, the boiling delay model would also be applicable, but this has up until now never been tried in literature. This is likely due to the importance of accurate bubble formation and growth equations, which are also impacted by short term mechanical non-equilibrium [26]. Lastly, the homogeneous relaxation model is a rather straightforward extension of the complete equilibrium assumption. It has been successfully used to describe complex systems. Recently, it has been implemented to describe the flashing process in a reciprocating expander [57]. However, experimental validation has to be conducted.

3. Experimental Available Data

The experimental data that have been published on two-phase expansion is hereafter summarized in this section. Firstly, the Lysholm expander will be elaborated on, as this type of expander has received the most attention in literature. Afterward, a brief look will be taken at static flash, as this type of flashing is closely related to what is happening in a reciprocating expander. Lastly, the available experiments on reciprocating expanders will be reviewed last.

3.1. Lysholm Expander

Table 1 shows the available experimental data on two-phase Lysholm expander. The used working fluid, power range, vapor quality range, and measured efficiencies. In the following, they will be compared to one another.

Table 1. Available literature about experimental Lysholm two-phase expanders.

	Working Fluid	Efficieny	Power	Vapor Quality
[59] (1975)	Water	49–55%	16–30 kW	0.12–0.34
[60] (1982)	Water	15–53%	1–60 kW	0.08–0.27
[61] (1982)	Brine	45%	1 MW	0–0.99
[46] (1993)	R113	over 70%	40 kW	-
[32] (1988)	R12	30–60%	10 kW	-
[43] (2013)	R134a	73–92%	50 kW	0.7–1

The screw (or Lysholm) expander is the most prevalent expander that has been studied experimentally in two-phase conditions. Ref. [59] was one of the earliest that published a dataset in 1975, several powers were tested ranging from 16 kW up to 30 kW. The efficiencies that were found for this engine do not come near the theoretical required value of 75% found by [13]. However, Lysholm machine technology has much improved over the years, primarily due to its compressor applications. The authors did not mention whether the vapor quality has an impact on the efficiency within the tested range of 0.12 to 0.34. Ref. [60] tested lower vapor qualities and only mentions an influence of the rotational speed of the screws and the back pressure on the measured efficiencies. Ref. [61] did field tests on a 1 MW screw installation over a range of vapor qualities from 0 to 1. The resulting efficiencies are on average around 45%, which are similar results as [59,60]. All previous experiments mentioned were performed with water as the working fluid. In the following, the reported data comes from the use of refrigerants. Ref. [32] used R12 while [62] executed their experiments with R113. They found efficiencies ranging from 40 to 70%. They concluded that the thermodynamic modeling techniques that are used for single-phase expanders could also be used for two-phase Lysholm expanders with some modifications. They also showed that similar efficiencies can be reached for single-phase and two-phase Lysholm machines. When comparing their efficiencies with single-phase experiments the same conclusions were made by [63]. Lastly, Ref. [43] performed tests with R134a as working fluid. The authors proposed a method to determine the adiabatic efficiency of two-phase operation based solely on single-phase experimental data. This in function of the adiabatic efficiency with saturated vapor and the peak adiabatic efficiency together with the inlet vapor quality. The authors tested their theory on the data of [60–62]. They concluded that for these cases their theory was correct, but that the amount of data is not sufficient to make any firm claims.

3.2. Static Flash

Before going to the specific experiments with reciprocating expanders or piston expanders, static flashing will be introduced. These are similar to reciprocating expander experiments which will be discussed later. This means that the only difference between the reciprocating experiments and the static flash experiments is the load profile which dictates the pressure drop over time. Table 2 shows the experimental static flash data which will be discussed later in this section. Ref. [18] used R12 as the working fluid. The authors installed seven capacitance measurement units over the height of the flashing chamber to measure the void fraction profiles in the cylinder as a function of time when sudden depressurization occurs. It was concluded that the void fraction only linearly increases with respect to the height of the cylinder after around 1.5 s have passed, by which time most thermodynamic disequilibrium has been reduced. Ref. [20] performed experiments on flashing water with a constant initial liquid level of 15 mm and was able to construct a relation of proportionality between the final amount of flashed mass and the initial superheat of the liquid. This parameter is also found as an important quantity in the modeling techniques mentioned earlier. The authors also show that this proportionality can be derived from the heat balance within the flashing chamber. Their results are in good agreement with the results of [64] which performed similar experiments but with a higher initial liquid level. Later [21] also modeled the static flash phenomena and compared it with experiments on a wide variety of conditions in a rectangular enclosure. The authors concluded that the initial pressure has little effect on the flashed mass itself, it only affected the onset of flash evaporation, which is in accordance with previous research. Ref. [65] studied the amount of exergy that is lost due to flash evaporation, the authors concluded that most exergy loss can be avoided if the flashing process takes longer and has a lower superheat temperature of the flashing liquid, this result is beneficial for reciprocating expanders as the pressure drop takes place over a longer time period compared to static flash.

Table 2. Available literature about experimental static flashing.

	Working Fluid	Starting Pressure	Initial Liquid Level
[18] (1984)	R12	10.7 bar	600 mm
[20] (2002)	Water	0.05–0.2 bar	15 mm
[64] (1973)	Water	0.07-0.47 bar	196–225 mm
[21] (2019)	Water	0.05–0.3 bar	0.23–2.3 mm
[65] (2015)	Water	0.08–0.36 bar	100–300 mm

3.3. Reciprocating Expander

Only [38] have performed two-phase expansion experiments with a reciprocating engine. The working fluid used by the authors was water and later ethanol. These experiments are also very similar to static flash experiments with a slower pressure decrease. In the static flash experiments, the piston was suddenly connected to another larger vessel under vacuum conditions, resulting in larger depressurization rates compared to the experiments for reciprocating expanders. Here, the cylinder was loaded with liquid before the piston was set in motion using a linear actuator. The adiabatic efficiencies reached are in the range of 80–95% [38,48]. To compare with [43], the authors theoretically imposed mechanical and electrical losses, achieving a maximum adiabatic efficiency of around 80% which is similar as the Lysholm expander [49]. The authors also conclude that a two-phase reciprocating expander achieves similar efficiencies as a single-phase reciprocating expander.

3.4. Conclusions of Two-Phase Experimental Data

In general, the amount of experimental data on two-phase expanders is quite low considering the theoretically proven potential of some of its applications. Most of this available data was performed on the lysholm (screw) expander. These expanders are based on compressor design methods without a lot of adaptions. This is one area where more research has to be performed, the difference in the design of compressor and expander machines. The available data shows that the equilibrium assumption is sufficient to describe the process in these machines while this is not the case for the reciprocating type. Why this is the case is also only speculated and not yet conclusively shown. To study the flashing expansion phenomena itself, more research is required on other machine types where the liquid superheat is measurable.

4. Modeling of Two-Phase Volumetric Expanders

In the following section, an overview of models of two-phase volumetric expanders in open literature is summarized but first, the inlet and outlet flow valves are considered here shortly. These are often not taken into account or with a straightforward, often equilibrium, process. However, it is possible to also apply the non-equilibrium models here. For example, Ref. [66] used the HRM for this modeling of expander valves, where the authors were able to accurately predict the operation of the inlet and outlet valves independent of the vapor fraction and oil content.

4.1. Lysholm Expander

One of the first analytical models for the two-phase Lysholm expanders is described by [32]. The authors mostly assume thermodynamic equilibrium and thus apply the HEM. The authors compared their analytical model with their performed experiments. Both methods showed an increase in internal efficiency with the rotor speed. Importantly, the authors also looked into a flashing delay. Included by adding a certain time delay between the start of the intake stroke and instantaneous flashing to equilibrium. The authors conclude that this can be omitted as the results for no delay time correspond just as well to their experiments. A similar methodology to [32] was applied by [33]. However, compared to a broader experimental dataset. The authors showed that the working fluid choice and correct rotor profiles are important in the design of TLC with a twin screw expander. Ref. [45] created a chamber model for a twin-screw expander within commercial software with the capability of integration in an entire TLC cycle. This methodology is specific to the machine as it requires geometrical data regarding cell volume evolution, suction and discharge ports as well as the multiple leakage paths in Lysholm expanders [44]. This model also uses thermodynamic equilibrium properties, and thus applies the HEM. The authors found a significant impact of the intake manifold expansion on the overall machine performance. Therefore, the authors designed a Lysholm expander with a variable built-in volume ratio [67]. The simulations show higher total power outputs for smaller BVR due to the higher mass flow rates, while the specific power decreases. Lower BVR also results in higher volumetric efficiencies but lower isentropic efficiencies due to under-expansion. In general, the simulation is capable to optimize the total power output in different operation conditions by varying the BVR. Lastly, Ref. [34] also assumed thermodynamic equilibrium in their initial simulation procedure. Additionally, they also assume that the work is performed by the vapor phase. Later, Ref. [68] modeled the chambers with flash vaporization based on an equation found by experimental spray flash evaporation. This model assumes a minimum superheat of 1 K before evaporation occurs. The amount of evaporation is a fraction of the evaporation needed to achieve equilibrium which was experimentally determined. Thus a boiling delay model was used. The model with thermal disequilibrium predicted slightly lower internal power and isentropic efficiency, but only in the order of 3%. This is in line with the general finding that the equilibrium assumption can be used for Lysholm expanders.

4.2. Reciprocating Expander

After experimental determination of a temperature difference between the liquid and vapor phase, Ref. [47] constructed a five equation flashing model consisting of three energy continuity equations (of the liquid, vapor, and housing) combined with the mass continuity and the interfacial exchange model Equation (5) to predict the experimental data. Ref. [21] compared the model proposed by [47] with the HEM for different expander frequencies and initial superheats. The authors find discrepancies of up to 8% in the isentropic efficiency and expansion work between the two models. These are attributed to the disequilibrium losses by the authors. Ref. [69] proposed a design for a two-phase reciprocating expander consisting of a cyclone separator and the piston itself. The applied modeling for this design was also based on equilibrium assumptions. The authors found isentropic efficiencies in the range of 65 to 85% depending on the working fluid and operational regime. They also noted lower efficiencies for higher engine speeds. Ref. [54] used this design with the model of [47] to estimate the intake losses. For this design, the authors found a linear relation between the intake losses and the intake ratio, defined as the intake time to the expansion time. Ref. [19] also modeled a two-phase expander with a cyclone separator. The authors applied an evaporation model based on static flash pool evaporation and separated the phases in the cyclone and piston parts. Due to the better predicted performance at higher evaporation rates, the authors consider rotary expanders a better match for the two-phase expansion process.

4.3. Conclusions of Two-Phase Expander Modeling

Screw expanders have seen the most modeling of their use with two-phase expansion. Most of these assumed thermal equilibrium throughout expansion as these conform well with the available experimental data. The impact of the inlet port was found to have a non-negligible impact on the operation of the machine. More research about the design of the inlet manifold for two-phase expanders would thus be advised instead of basing the design on the machines compressor operation. When flash evaporation within the chamber was assumed, a discrepancy of only 3% was found with the equilibrium model. Reciprocating expanders on the other hand do require some modeling technique that takes into account the metastable conditions. Only one model of this type was available which takes the metastable condition in the working chamber into account via the mixture model. Other models split up the working volume in the expansion chamber and a phase separator cyclone. This process will have to be studied further, and described with more methods, to better understand the phenomena. These insights could make it possible to better design two-phase volumetric expanders.

5. Conclusions

The current review shows the possibilities and state-of-the-art of two-phase volumetric expansion machines. Research is scarce but promising results are presented. The most notable application for volumetric two-phase expanders is in low-temperature heat-to-power cycles. These cycles have around 20% higher exergy efficiency for power production comapred to the basic organic Rankine cycle if efficient volumetric expansion machines are available. The required efficiencies of 75% are achievable, as was experimentally shown. However, consistent design and simulation models are still unavailable. This requires more research and a better understanding of the process and the occurring phenomena. The modeling of these types of machines is complex. For screw expanders, it was experimentally shown that it can be assumed that the phases are in thermal equilibrium, which implies that the vapor and liquid have the same temperature. Researchers simulate this type of two-phase expander with the use of the homogeneous equilibrium model. The available experimental data is predicted well by these models. On the other hand, it was shown that the thermal equilibrium cannot be assumed for reciprocating expanders. Experimental data and models are very limited for this type of expander. The only available data for reciprocating expanders was described with the use of the mixture model. Another rather simple technique to describe the metastable condition is the homogeneous relaxation model which has been shown to give promising results in other processes, including over inlet and outlet valves. Lastly, the boiling delayed model could also be applied, but presently this was not implemented due to the complexity of the technique and required understanding of the phenomena occurring.

In the near future more research and progress are expected in this area. This increase in interest is likely due to its main predicted application and its need in current times. More work in understanding the principles of flashing in the specific case of volumetric expanders should be performed. Initially, this can be inspired by methods of other flashing phenomenon. Primarily, those where mechanical equilibrium is assumed. For example, the boiling delay model has never been applied to any volumetric expander. Not only does the theoretical understanding need more research, experimental research requires more work as well. Currently, it mostly occurs on lysholm expanders and the experiments are few and far between. More experimental data is required and on a multitude of different expander types. The impact of design parameters on these experiments has to be studied as well.

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Abbreviations

The following abbreviations are used in this manuscript:

BLEVE	Boiling Liquid Expanding Vapor Explosion
EOS	Equation of State
LNG	Liquefied Natural Gas
VPT	Variable Phase Turbine
ORC	Organic Rankine Cycle
TLC	Trilateral Cycle
PEORC	Partial Evaporation Organic Rankine Cycle
BVR	Built in Volume Ratio
HEM	Homogeneous Equilibrium Model
HRM	Homogeneous Relaxation Model
WORC	Wet Organic Rankine Cylce

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