Theoretical investigation of flash vaporisation in a screw expander

Hanushan Vasuthevan, Andreas Brümmer
TU Dortmund University, Chair of Fluidics
Leonhard-Euler-Str. 5, 44227 Dortmund, Germany
hanushan.vasuthevan@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de

Abstract. In the present study flash vaporisation of liquid injection in a twin screw expander for a Trilateral Flash Cycle (TFC) is examined theoretically. The TFC process comprises a pressure increase in the working fluid, followed by heating the liquid close to boiling point. The hot liquid is injected into the working chamber of a screw expander. During this process the pressure of the liquid drops below the saturation pressure, while the temperature of the liquid remains virtually constant. Hence the liquid is superheated and in a metastable state. The liquid jet seeks to achieve a stable state in thermodynamic equilibrium and is therefore partially vaporised. This effect is referred to as flash vaporisation. Accordingly, a two-phase mixture, consisting of vapour and liquid, exists in the working chamber. Thermodynamic simulations were carried out using water as the working fluid for representative screw expander geometry. The simulations presented are performed from two different aspects during the filling process of a screw expander. The first case is the vaporisation of the injected liquid in a state of thermodynamic equilibrium, whereby the two-phase mixture is treated entirely as a compressible and homogeneous gas. The second case considers flashing efficiency. It describes the quantity of flashed vapour and consists of a liquid and vapour domain. Both models are compared and analysed with respect to the operational behaviour of a screw expander.

1. Introduction
The Trilateral Flash Cycle (TFC) is a suitable opportunity for power recovery from low-temperature sources such as geothermal sources or industrial waste heat. Compared to the Clausius Rankine Cycle or the Organic Rankine Cycle the Trilateral Flash Cycle does not need vaporisation or superheating of the working fluid. The TFC contains basically only liquid heating close to boiling point and vaporisation during expansion into the wet vapour region, which is referred to as flash vaporisation. Flash vaporisation occurs if a liquid undergoes a sudden reduction in pressure, while the temperature is virtually constant. In this state the temperature is higher than the saturation temperature at its current reduced pressure. Hence the liquid is superheated and in a metastable state. In order to regain a more stable state in thermodynamic equilibrium, part of the liquid is vaporised, which can occur explosively and violently depending on boundary conditions. Consequently a two-phase mixture with high liquid content exists during the expansion process. For this expansion process a screw expander is suitable. Unlike turbomachines, screw expanders are able to expand multiphase fluids with high liquid content. In the past, screw expanders in a TFC were primarily examined experimentally. A literature survey is given in [1]. Detailed methods or models for the design of a two-phase screw expander for a trilateral flash cycle are not available, although this technology seems to have a high efficiency potential. The comprehension of the inner process in a liquid injected two-phase screw expander with flash
vaporisation is an important requirement if the efficiency is to be maximised. One essential part of a screw expander working cycle is the filling process, which involves hot liquid injection into the working chamber. During this injection via a nozzle a superheated liquid jet is formed, which is partially vaporised in the working chamber due to flash vaporisation.

The main objective of this paper is to investigate the flash vaporisation of a superheated liquid jet in a twin screw expander theoretically. For this purpose fundamentals of the flash vaporisation process will be described first. For the modelling of the flash vaporisation of a liquid jet a simple empirical model will be used. The simulations are carried out with the working fluid water for a single representative screw expander geometry. They are performed ideally without consideration of gap flows, to investigate the effect of the liquid jet on the working cycle. Two cases will be considered in the simulation. The first case considers the flash vaporisation in thermodynamic equilibrium. In this case the two-phase mixture is treated as a homogeneous and compressible gas. The second case includes flashing efficiency, which describes the vaporised mass flow rate, whereby the phases are considered separately with liquid and homogeneous wet-vapour domains. Finally, the results of the simulations will be described and discussed.

2. Flash vaporisation of superheated liquid jets

Flash vaporisation of superheated liquids has a variety of practical applications. One application among others is for example the desalination of salt water, whereby steam is generated and condensed to remove minerals from salt water. Further applications are e.g. fuel injection in engines, drying processes such as paper drying, geothermal power plants generating steam for turbines, etc. [2]. Compared to the targeted use of flash vaporisation these less controlled processes can be undesirable and hazardous, causing the accidental relaxation of liquids which can lead to explosions in piping systems, valves or vessels. One important example is the loss of coolant accident (LOCA) in nuclear power plants, whereby the pressure in the cooling system drops suddenly and the superheated coolant is vaporised explosively. The various desirable and undesirable practical applications of flash vaporisation have led to many publications. An extensive literature survey of flashing liquid jet studies is given in [3]. In the following the focus is on the essential fundamentals and modelling methods for the flash vaporisation of superheated liquid jets.

2.1. Fundamentals

A superheated liquid jet can be formed when the liquid is injected through a nozzle into a gaseous chamber with a pressure lower than the inlet pressure. During injection and at the nozzle exit the pressure drops while the temperature of the liquid is nearly constant. Consequently the temperature of the liquid is higher than its saturation temperature corresponding to the chamber pressure. Vice versa the pressure of the chamber is lower than the saturation pressure corresponding to the liquid temperature. This situation is shown in figure 1 in a pressure-temperature diagram. As a consequence the liquid is brought into a metastable state. The infiltration of the liquid into the metastable state can be described as superheating $\Delta T_{sh}$. In equation (1) the general definition for the superheating is given as the difference between the liquid temperature and the saturation temperature at the ambient pressure. For the liquid entering the chamber, the superheating is only a function of the chamber pressure which varies with time, when the inlet temperature of the liquid is constant. The maximum superheating for a given chamber pressure can be achieved if the inlet temperature is equal to the saturation temperature, which corresponds to the inlet pressure.

$$\Delta T_{sh} = T_{liq} - T_{sat}(p_{ch})$$

Under specific conditions without physical disturbances the metastable state can be maintained to a certain extent, depending on boundary conditions. In most practical situations the liquid goes through a transient vaporisation process to achieve thermodynamic equilibrium. During this process the temperature of the liquid decreases due to the energy consumption required for vaporisation. While the superheating of the injected liquid is only a function of the time-dependent chamber pressure, the
superheating of the liquid jet in the chamber depends on the local liquid temperature of the jet and the chamber pressure. Both these parameters vary with time.

The flash vaporisation process of the superheated liquid jet can be divided into four steps [4]. The first step is the nucleation process, which is a concentration process of molecules of the new or vapour phase to stable nuclides. The second step is the bubble growth of the stable nuclides. After that, the bubble growth within the jet leads to its breakup or atomisation, which leads further to ligaments and droplets. The last step is the vaporisation of the droplets.

![Figure 1. Change of state in a pressure-temperature diagram for a nozzle flow with liquid](image)

2.2. Modelling methods

There are different modelling methods for flash vaporisation with variable modelling depth, which can be adapted for different numerical calculation methods. In general, flash vaporisation can be divided into two modelling sections: atomisation and vaporisation. Modelling flash atomisation delivers information about the droplets such as distribution, diameter, number, temperature and velocity. The droplets are then adapted into the modelling of droplet vaporisation. To model atomisation, empirical correlations derived from experiments can be used. Another approach with higher modelling depth is to simulate the nucleation process by means of the classical nucleation theory and subsequent consideration of bubble growth and break-up to acquire information about droplets. Existing vaporisation models of droplets are based essentially on heat fluxes between droplets and their surroundings. These models also contain empirical correlations in order to determine, for example, heat transfer coefficients. A valuable review for modelling of atomisation and vaporisation is given in [4] and [5]. Another approach with a lower modelling depth is to determine the vaporised mass due to the flash vaporisation directly in terms of flashing efficiency, which is derived from experimental results. Miyatake presented such a model with an empirical equation for the working fluid water which depends entirely on superheating [6]. This model is used and adapted for the simulation of vaporisation in a screw expander (Section 3).

3. Modelling of the flash vaporisation in a twin screw expander

In this section modelling of flash vaporisation in a screw expander by means of an empirical model is described. Therefore first of all the fundamentals of the screw expander are described. Next, the modelling procedure for the screw expander is explained.

3.1. Fundamentals

Twin screw expanders are rotary displacement machines with spirally shaped intermeshing rotors enclosed in a housing. Clearances between the rotors within the enclosed housing form the working chambers, whose volume changes periodically due to the rotation of the rotors. The progression of the
chamber volume as well as idealised inlet and outlet areas for the present simulations, as functions of the male rotor angle, are shown in figure 3 (Section 4.1). The working cycle is divided into three steps. The first step is the filling process, where the working fluid from the high pressure side is transferred to the working chamber, while the volume of the working chamber increases. After the filling process ends there is no connection between the high pressure side and the working chamber. Thus, the working chamber - except for clearances - is enclosed from the environment. At this point the expansion process begins and proceeds as the rotors continue to turn. This process ends when the working chamber reaches its maximum volume. The working chamber is then connected to the low pressure side via the outlet area. At this point the discharge of the working fluid begins, while the chamber volume decreases during the third phase of the working cycle. The working cycle ends with the disappearance of the chamber volume.

3.2. Modelling procedure
For the simulation and its thermodynamic modelling a one-chamber model is used, where the rotors of a twin screw expander (male rotor and female rotor) are considered together. The calculations are mainly based on the conservation of mass and energy which are derived separately for a homogeneous gas phase and a liquid phase. This approach offers the option of examining thermodynamic non-equilibrium states within working chambers. The conservation equations for a stationary system are given in [1]. The basic simulation procedure is as follows: For a given time step or male rotor angle the geometry of the screw expander will be considered as a frozen model. It therefore follows that chamber volumes and flow areas between working chambers and ports are defined. Within this time step numerical integrations of the conservation equations are performed. In the present paper the simulations are carried out ideally without clearances. Furthermore heat flows between fluid and solid components are ignored. In the simulations the inlet flow, outlet flow and the flash vaporisation of the injected liquid within a working chamber are considered. In the following, modelling of the essential processes is described.

3.3. Liquid injection
The filling process involves the injection of a hot liquid from the high pressure side into a chamber volume via a nozzle. The calculation of the mass flow rate is carried out by means of the Bernoulli equation for steady and incompressible flows from point 1 (reservoir upstream of the nozzle) to point 2 (nozzle outlet exit), which is given in equation (2), ignoring geodetic height differences and friction losses.

\[
\frac{p_1}{\rho} + \frac{c_1^2}{2} = \frac{p_2}{\rho} + \frac{c_2^2}{2}
\]

(2)

Kinetic energy in point 1 can be ignored. At point 2 pressure \(p_2\) is assumed to be equal to the pressure in the working chamber which is to be filled. The pressure in the working chamber changes with time or male rotor angle, which leads to a step response and also a change in the nozzle exit velocity in the simulation. With equation (2) the theoretical maximum injection mass flow rate can be determined with density \(\rho\) and nozzle exit area \(A\). Taking losses from point 1 to point 2 into account will reduce the theoretical maximum mass flow rate. Therefore the losses are included with a flow coefficient \(\alpha\). The actual mass flow rate for the injection of liquid into the working chamber can be calculated with equation (3).

\[
\dot{m}_{\text{inj}} = \alpha \dot{m}_{\text{th}} = \alpha \rho A \sqrt{\frac{2}{\rho} (p_1 - p_2)}
\]

(3)

3.4. Flash vaporisation of superheated liquid
The liquid in the working chamber is vaporised partially due to flash vaporisation. The modelling of flash vaporisation is performed with an empirical equation for the working fluid water which was
developed by Miyatake [6]. Miyatake examined the transient spray flash evaporation characteristics of a desalination system experimentally. Although the time-scale used by Miyatake is far greater than the time-scale of a typical screw expander working cycle, this model will be used to examine the effects in a screw expander due to its simplicity and general application. The model contains a flashing efficiency, which is defined as the ratio of the vaporised mass flow rate to the maximum mass flow rate. In equation (4) the definition and the empirical equation for the flashing efficiency are given, which depends entirely on the superheating. Miyatake figured out that this equation corresponds quite well with his experiments for various nozzle velocities, nozzle lengths and nozzle diameters. With increasing superheating the flashing efficiency tends towards one. Furthermore equation (4) is only valid for superheating equal to or greater than one.

$$\eta_{\text{flashing}} = \frac{\dot{m}_{\text{vap}}}{m_{\text{vap,max}}} = 1 - \left[ 1 + 2.5 \left( \frac{\Delta T_{\text{sh}}}{K} - 1 \right) \right]^{-1} \quad \forall \Delta T_{\text{sh}} \geq 1K$$  \hspace{1cm} (4)

The theoretical maximum mass flow for the vapour generation can be calculated with equation (5), which is derived from conservation of energy. Here it is assumed, that the vapourised mass flow is in a saturated state. The maximum mass flow of vapour is generated when after vaporisation the liquid reaches the saturation temperature in thermodynamic equilibrium, corresponding to its chamber pressure.

$$\dot{m}_{\text{vap,max}} = \dot{m}_{\text{liq}} \frac{h_{\text{liq}}(T_{\text{liq}}) - h_{\text{liq}}(T_{\text{sat}}(P_{\text{ch}}))}{h_{\text{vap}}(T_{\text{sat}}(P_{\text{ch}})) - h_{\text{liq}}(T_{\text{sat}}(P_{\text{ch}}))}$$ \hspace{1cm} (5)

In figure 2 flash vaporisation in a chamber is illustrated. The chamber contains two general domains. The first domain is the vapour domain, which is in a single state and can be a superheated gas or a homogeneous wet-vapour mixture. This domain is treated entirely as a compressible gas and is calculated in thermodynamic equilibrium. The second domain is the liquid domain, which is incompressible and occupies the chamber volume in part. This domain contains a certain number of liquid elements $n$, which results from the liquid injection. For every time step in the simulation during the filling process a liquid element is created. Each liquid element has a different individual state. The detailed conservation equations of mass and energy for both domains which are used for the simulation, are given in [1]. In the following the calculation procedure for flash vaporisation within the chamber, with mass and energy transfer between the two domains for a time increment $\Delta t$, is described without further analysis.

Within the time increment every liquid element of the liquid domain is considered. First the superheating for a liquid element is determined, which depends on the pressure in the chamber and the temperature of the liquid element. For liquid elements with superheating greater than one, the flashing efficiency is calculated, which is then multiplied with the maximum mass flow rate in equation (5) to determine the actual mass flow rate of vaporisation from a liquid element. The vapourised mass of a liquid element is calculated with numerical integration of the mass flow rate of vaporisation and a time increment as shown in equation (6). With equation (7) the heat due to vaporisation can be calculated, assuming that the vapourised mass is in a saturated state. In the case of superheating lower than one, the appropriate liquid element will not be considered.

$$\Delta m_{\text{vap,n}}(t_j) = \dot{m}_{\text{vap,n}} \Delta t = \eta_{\text{flashing,n}}(t_j)m_{\text{liq,n}}(t_j) \frac{h_{\text{liq,n}}(T_{\text{liq,n}}(t_j)) - h_{\text{liq}}(T_{\text{sat}}(P_{\text{ch}}(t_j)))}{h_{\text{vap}}(T_{\text{sat}}(P_{\text{ch}}(t_j))) - h_{\text{liq}}(T_{\text{sat}}(P_{\text{ch}}(t_j)))}$$ \hspace{1cm} (6)

$$\Delta Q_{\text{vap,n}}(t_j) = \Delta m_{\text{vap,n}}(t_j) h_{\text{vap}}(T_{\text{sat}}(P_{\text{ch}}(t_j))) \quad \forall \Delta T_{\text{sh,n}} \geq 1K$$ \hspace{1cm} (7)

Due to the vaporisation of liquid elements and the resulting energy flow from liquid elements to the vapour domain, the temperature of liquid elements drops. If the superheating is high and the flashing efficiency is near one, the temperature of the liquid element may drop below the vapour domain temperature. In this case a heat flow would occur from the vapour domain to the liquid element. A
heat flow model for this case is not considered explicitly, but instead it is assumed that the affected liquid element is atomised very finely and has sufficient heat transfer to be homogeneous and in thermodynamic equilibrium within the vapour domain. Thus, the liquid elements involved are transferred completely to the vapour domain. In this case the transferred mass and heat to the vapour domain is given in equation (8) and equation (9).

\[ \Delta m_{\text{vap},n}(t_j) = m_{\text{liq},n}(t_j) \quad \forall \quad T_{\text{liq},n} < T_{\text{vap}} \]  
\[ \Delta Q_{\text{vap},n}(t_j) = U_{\text{liq},n}(t_j) \quad \forall \quad T_{\text{liq},n} < T_{\text{vap}} \]  

The mass transfer within a chamber and between the two domains is performed with the calculated vapour mass, which is subtracted from the corresponding liquid element as given in equation (10). The sum of the vapour mass from all liquid elements under consideration is added to the vapour domain as shown in equation (11).

\[ m_{\text{liq},n}(t_j) = m_{\text{liq},n}(t_{j-1}) - \Delta m_{\text{vap},n}(t_j) \]  
\[ m_{\text{vap}}(t_j) = m_{\text{vap}}(t_{j-1}) + \sum_n \Delta m_{\text{vap},n}(t_j) \]  

Furthermore the transferred heat due to the vaporisation between the two domains is dealt with in equations (12) and (13).

\[ U_{\text{liq},n}(t_j) = U_{\text{liq},n}(t_{j-1}) - \Delta Q_{\text{vap},n}(t_j) \]  
\[ U_{\text{vap}}(t_j) = U_{\text{vap}}(t_{j-1}) + \sum_n \Delta Q_{\text{vap},n}(t_j) \]  

It should be noted that the above equations only describe the mass and heat transfer due to the flash vaporisation between the liquid and vapour domains. For the simulation of the screw expander the complete mass and energy conservation equations are used, as given in [1].

\[ c_{\text{vap,out,is}}(t_j) = \sqrt{2 \cdot (h_{vap,\text{ch}}(t_j) - h_{\text{lp}})} = c_{\text{liq,out,is}}(t_j) \]  

For the calculation of the mass flow, the flow area for the two domains is different. Here, it is assumed that the flow area is divided, corresponding to the volume of the domains in the chamber. With the
volume fraction of the vapour domain in the chamber, which is shown in equation (15), the mass flows for both domains are calculated. In equation (16) and equation (17) the actual mass flow is shown, resulting from the multiplication of theoretical maximum (isentropic) mass flow and flow coefficient, taking losses into account.

\[
\epsilon(t_f) = \frac{v_{\text{vap}}(t_f)}{v_{\text{cal}}(t_f)} \tag{15}
\]

\[
\dot{m}_{\text{vap, out}}(t_f) = \alpha \dot{m}_{\text{vap, out,is}}(t_f) = \alpha \epsilon(t_f) A(t_f) \rho_{\text{vap}}(t_f) c_{\text{vap, out,is}}(t_f) \tag{16}
\]

\[
\dot{m}_{\text{liq, out}}(t_f) = \alpha \dot{m}_{\text{liq, out,is}}(t_f) = \alpha (1 - \epsilon(t_f)) A(t_f) c_{\text{liq, out,is}}(t_f) \tag{17}
\]

4. Simulation

First of all the boundary conditions and the assumptions for the simulations are presented. Subsequently the results are shown and explained.

4.1. Boundary conditions and assumptions

In figure 3 the geometry of the simulated machine is given. The inlet and outlet areas are idealised as rectangular functions. The flow coefficients for each flow are set at one and treated as ideal. Compared to typical screw expanders the inlet area is designed as a circular area due to the innovative consideration that the liquid is injected via a circular nozzle by means of an injection system. The diameter of the nozzle exit is \(d_{\text{nozzle}} = 5\, \text{mm}\). Injection is started at a male rotor angle of \(35^\circ\) to avoid direct injection onto the front surface of the rotors. Injection is concluded at \(97^\circ\), which is equal to an internal volume ratio of \(v_i = 8\). The simulations are performed ideally without clearances. Furthermore heat flows due to a temperature difference between phases and solid parts are not considered. Two calculation models are analysed. The first model consists of one homogeneous vapour domain which is treated as a compressible gas. The state of this domain can be superheated or in the wet-vapour region and is calculated in thermodynamic equilibrium. This model will be abbreviated as HTEM (Homogeneous Thermodynamic Equilibrium Model) in the following. The second model consists of a liquid domain with a certain number of liquid elements and a homogeneous vapour domain, which is described in section 3.4. This model, which deals mainly with mass and heat transfer between the two domains due to flash vaporisation, will be abbreviated as FVM (Flash Vaporisation Model) in the following. Furthermore, any interactions between the injected liquid and rotor or casing walls are not taken into account. Simulations were carried out for the following conditions:

- **inlet:**
  - \(p_{\text{in}} = 10\cdot10^5\, \text{Pa}\)
  - \(T_{\text{in}} = 453\, \text{K}\)
  - \(u_{\text{male}} = 30\, \text{m\,s}^{-1}\)

- **outlet:**
  - \(p_{\text{out}} = 1\cdot10^5\, \text{Pa}\)
  - \(T_{\text{out}} = 373\, \text{K}\)

![Figure 3. Screw expander geometry with volume and area curves](image-url)
4.2. Results

In figure 4 the pressure curve depending on the male rotor angle for HTEM and FVM is shown. The dashed line represents the pressure curve from HTEM and the continuous line shows the pressure curve from FVM. Integral values are also shown in the diagram. It can be seen that internal power, internal work and internal isentropic efficiency are slightly reduced for the FVM compared to the HTEM. The difference in values between the two models is less than 3%.

Nevertheless the essential differences between the two models are still worth describing. The progression of mass in the chamber and the steam content of the vapour domain during the working cycle for both models can be seen in figure 5. The FVM includes the liquid and vapour domain, compared to the HTEM, which only includes one vapour domain. During the injection and expansion process it can be seen that the mass of the liquid domain decreases, while the mass of the vapour domain increases, due to flash vaporisation and mass transfer between the domains. The sum of the liquid domain mass and the vapour domain mass remains constant during the expansion process. For the HTEM the mass in the chamber increases during injection and remains constant during the expansion process up to the discharge process. The mass of the vapour domain for the FVM is smaller than for the HTEM because the liquid elements are in a separated domain. The volume of the vapour domain remains nearly constant for both models due to the high density of liquid water. Therefore the density of the vapour domain for the FVM is smaller, thus influencing the pressure in the chamber. Due to the lower density of the vapour domain the pressure progression in the chamber is slightly smaller during the injection and expansion process for FVM compared to HTEM. This results in the reduced internal work for FVM.

![Figure 4](image-url)

**Figure 4.** Pressure curve depending on male rotor angle for the homogeneous thermodynamic equilibrium model and flash vaporisation model (Miyatake)

In figure 5 it can be seen by means of the steam content, that the fluid of the vapour domain for both models is a wet vapour mixture, except for the beginning of injection for the FVM, where the state of the fluid is saturated vapour. Furthermore it can be seen, that the steam content of the vapour domain is higher for the FVM compared to HTEM. The reason for this is that beside the vapour domain a liquid domain exists, where the liquid elements remain. Due to the higher steam content of the vapour domain for the FVM, the specific enthalpy in the chamber is higher compared to the HTEM. Therefore a higher velocity is calculated for the discharge flow by means of conservation energy. The consequence of this can be seen at the beginning of the discharge process from a male rotor angle of 345° in figure 4. In case of the FVM, the pressure decreases faster to the low pressure side than in the case of HTEM. This increases the internal work for the FVM compared to HTEM.
In the following the reason for the small difference of the pressure angle curve in figure 4 between both models will be outlined by means of the results from FVM. In figure 6 temperature curves and flashing efficiency for the liquid entering the chamber are shown. As injection begins, the pressure inside the chamber is low, so that the corresponding saturation temperature $T_{\text{sat}}$ is also low, while the temperature of the injected liquid $T_{\text{in}}$ remains constant at the moment of entering the chamber. So there is high superheating for the liquid entering the chamber, which leads to high flashing efficiency. The pressure increases rapidly at the start of injection due to the small chamber volume, leading to smaller flashing efficiency for the liquid entering the chamber. From a male rotor angle of about 50° the pressure decreases due to the volume increase during injection. Hence the saturation temperature for the corresponding chamber pressure decreases as well. This leads to increased superheating and flashing efficiency for liquid entering the chamber at the end of the injection process. The flashing
efficiency during injection is very high, which leads to vaporisation close to thermodynamic equilibrium.

5. Conclusions
The main objective of the present paper is to examine the flash vaporisation of a superheated liquid jet in a screw expander. For this purpose, a representative screw expander geometry was simulated. Two different cases were considered. In the first case, as a reference, the screw expander was simulated with one chamber domain, where the working fluid was treated entirely as a homogeneous compressible gas in thermodynamic equilibrium. The second case consists of two domains and considers flashing efficiency, which was derived from experiments [6] and describes the amount of vaporised substance depending on superheating. Although the model has not yet been confirmed for the time scale of a screw expander, it has been used to analyse the basic effects. The simulations were carried out ideally with a one chamber model without clearances in order to examine in isolation the effect of the superheated liquid jet in a screw expander. Furthermore, heat flow and momentum transfer between working fluid and solid parts were not considered. For the point of operation under examination it has been shown that internal work and internal isentropic efficiency are higher for the first case. In the case of flashing efficiency less mass is vaporised compared to the first case, which influences the pressure progression and leads to reduced internal work. Furthermore, at the beginning of the discharge phase, low pressure is achieved faster in the second case, which results in an increase in internal work. To sum up, the difference between the integral values in the two cases is less than 3%, which results from high flashing efficiency during injection.

List of symbols and abbreviations

| Symbols | Abbreviations |
|---------|---------------|
| A       | area (m²)     |
| c       | velocity (ms⁻¹) |
| h       | specific enthalpy (Jkg⁻¹) |
| m       | mass flow (kgs⁻¹) |
| p       | pressure (Pa) |
| T       | temperature (K) |
| t       | time (s) |
| V       | volume (m³) |
| u       | circumferential speed (ms⁻¹) |
| v₁      | internal volume ratio (-) |
| α       | flow coefficient (-) |
| ε       | volume fraction (-) |
| η       | efficiency (kgm⁻³) |
| ρ       | density |
| ch      | chamber |
| i       | internal |
| in / out| inlet / outlet |
| inj     | injection |
| is      | isentropic |
| j       | simulation step |
| liq     | liquid |
| lp      | low pressure side |
| max     | maximum |
| n       | number of liquid elements |
| sat     | saturation |
| sh      | superheat |
| th      | theoretical |
| vap     | vapour |

References

[1] Vasuthevan H and Brümmer A 23rd International Compressor Engineering Conference at Purdue paper 1432
[2] El-Fiqi A K, Ali N H, El-dessouky H T, Fath H S and El-Hefni M A 2007 Desalination 206 311-321
[3] Polanco G, Hold A E and Munday G 2010 Journal of Hazardous Materials 173 2-18
[4] Kamoun H 2014 Flash-atomization and vaporisation at near vacuum conditions-Dissertation University of Stuttgart
[5] Aggarwal S K and Peng F 1995 Journal of Engineering for Gas Turbines and Power 117 453-461
[6] Miyatake O, Koito Y, Tagawa K and Maruto Y 2001 Desalination 137 157-166