Performance Improvements of Scroll and Sliding Vane Expanders Via a Double Intake Port Technology for ORC-Based Power Units

Fabio Fatigati and Roberto Cipollone

Abstract Sliding Vane Rotary (SVRE) and Scroll machines are the most referenced Expanders for small scale Organic Rankine Cycle (ORC)-based power units. Indeed, volumetric expanders are generally preferred to the dynamic ones as they better address severe off-design conditions. Nevertheless, they present some intrinsic limitations related to friction, volumetric performance and geometrical constraints. Moreover, these machines behave like an "equivalent rotating valve" and their permeability (relationship between flow rate and pressure drop) primarily depends on the in taken mass flow rate. In this paper a Double Intake Port (DIP) technology is considered to achieve important benefits in terms of expander performance. DIP involves that after the closure of the main intake port, an additional port is opened fed by the working fluid at the same thermodynamic conditions of the first port. Thanks to this new aspiration, the pressure inside the vanes increases and, therefore, the indicated power as well as the capability of the machine to aspirate a greater quantity of fluid. A lumped effect of the DIP technology is the increase of the permeability of the expander able to elaborate a higher mass flow rate for a given pressure difference. The efficiency of the original and DIP machines is discussed as well as the effects on the on the power produced. To perform this analysis, comprehensive theoretical models of both expanders were carried out and experimentally validated. Subsequently, the models were used as a software platform to assess a best design of the DIP expanders in terms of performances.

Keywords Small scale ORC based power unit · Scroll expander · Sliding Rotary Vane expander · Dual intake port · Design optimization

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1 Introduction

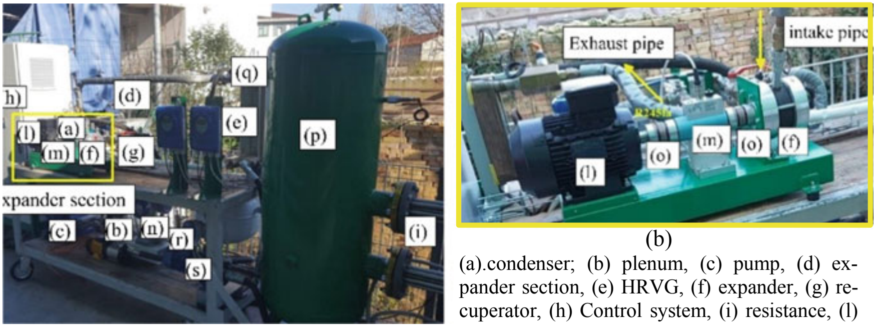
Organic Rankine Cycle (ORC)-based power units are interesting and promising solutions to produce mechanical power recovering low and medium grade heat, [1]. These power plants allow to exploit low temperature renewable heat sources such as solar [2], geothermal [3] and biomasses combustion [4]. Moreover, it is widely used for Waste Heat Recovery in Internal Combustion Engines [5] and in the Industrial Sector [6] too. In such application, volumetric expanders are chosen for the low rotational speed, the capability to elaborate two-phase working fluids and low mass flow rates for high pressure ratio, [7]. The selection of a volumetric expander depends by many factors, and it is not possible to define an optimal technological solution for every situation, [7]. The most important technological alternatives are those based on Scroll [8], Screw [9], Piston [10] and Sliding Rotary Vane machines [11]. Among these technological alternatives, Scroll and Sliding Rotary Vane expander are widely used but they present low capacity, [9]. Among the technology allowing to improve the performance of these machines and in general of all volumetric devices, the Dual Intake Port (DIP) is one of the most effective [11–13]. The authors demonstrated in previous works as, when it was introduced in Sliding Rotary Vane Expander, DIP technology ensures to increase the mass flow rate elaborated by the machine and consequently the power produced, [11, 12]. In [13] the authors provide a feasibility analysis of DIP technology when it was applied to scroll expanders. In the present paper, the benefits of the DIP technology were assessed when this technology was applied to SVRE and Scroll expander employed in a solar driven ORC-based unit for micro-cogeneration, and more in general, in those application characterized by a low temperature of the hot source and in all the cases of very reduced mechanical power recovered.

2 Materials and Methods

A wide experimental characterization was carried out on Sliding Rotary Vane and Scroll expander introduced on a fully instrumented ORC-based power unit (Fig. 1a) where the working fluid is R245fa. An amount of ISOVG 68 POE oil (5% of the working fluid mass) was mixed to the working fluid to fulfill the lubrication and sealing requirements of the pump and the expander. The analyzed recovery unit was developed for micro-cogeneration purposes. Indeed, it was conceived to be integrated to flat solar thermal collector for the simultaneous production of heat and electric power. In the experimental facility, the solar power is reproduced by two electric resistances (i) (12 kW each one) heating up 135 L of hot water stored in a Thermal Storage Tank (TES) (p). The hot water represents the hot source of the ORC power unit. It is delivered by a water pump (q) towards a Heat Recovery Vapor Generator (HRVG) (q) thus providing thermal power to the working fluid (R245fa) entering the HRVG cold side. R245fa leaves the HRVG as a 15 °C superheating degree vapor and enters the expander (f). According to the choice of the expander machine (SVRE of Scroll) the experimental layout slightly changes. If SVRE is employed (Fig. 1b), the expander is externally linked to the electric motor (l) through mechanical joint (o) and torquemeter (m). The electric motor is then connected to the electric network. Such architecture together the adoption of a regenerative inverter, ensures to control the expander speed which is an important degree of freedom in the recovery plant regulation. Indeed, the speed variation allows to regulate the machine permeability, defined as the ratio of pressure difference at expander sides and mass flow rate entering the machine. So, the higher is the revolution speed the higher is the permeability and lower the expander intake pressure for a given mass flow rate and expander outlet pressure. In fact, a volumetric expander can be seen as a revolving valve defining the evaporating pressure of the ORC unit, [14]. If scroll expander is adopted, the plant layout changes in the expander section (Fig. 2). Indeed, as reported in Fig. 2, the scroll machine shares the shaft with the electric motor and both elements are enclosed in the same shaft being the machine hermetic. The electric motor is connected to a dissipative electric load without any link to the electric network. In this case the revolution speed is not externally controlled but is demanded to the dynamic equilibrium between the motor and resistance torque on the expander shaft. In both configurations at the outlet of the expander is placed a further heat exchanger (REX) (g) to perform a regeneration stage. It is important to notice how before to be sucked by the pump, the working fluid exiting the condenser (a) is gathered in a 3 L plenum (b) placed to dump the mass flow rate fluctuation, [14].

The wide experimental database ensures to assess the expanders performance and to validate their models. So, after the model validation, the two models are used as software platform to analyze the benefits introduced by the DIP technology in SVRE and Scroll expanders.

The SVRE theoretical model was obtained updating for the expander at hand (Fig. 3) the one developed by the authors in [11, 12]. The scroll model was instead



(a)

(b)

(a).condenser; (b) plenum, (c) pump, (d) expander section, (e) HRVG, (f) expander, (g) recuperator, (h) Control system, (i) resistance, (l) electric generator, (m) torquemeter, (n) Coriolis flow meter fm, (o) joint, (p) TES, (r) Magnetic fm, (s) hot water pump;

Fig. 1 ORC-based power unit **a**, Sliding Rotary Vane expander configuration **b**

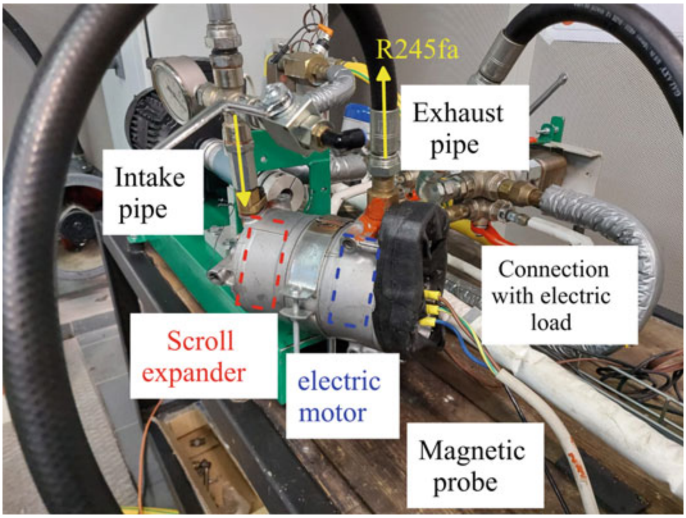


Fig. 2 Scroll expander configuration

obtained updating a previous version [13] for the analysed scroll expander (Fig. 4). Both models are developed in GT-Suite™ software platform thus integrating a zero 0-D and mono dimensional 1-D thermo-fluid-dynamic approach. The GT-Suite ™ model (Fig. 5) adopts the 1-D analysis to assess the dynamic phenomena taking place at intake (b) and exhaust pipes (d). Indeed, intake and exhaust pipes were discretized in multiple sub-elements and for each one the mass, momentum and energy equations are solved through an explicit integration method. Thus, the filling and emptying of the chambers (c) can be reproduced. The 0-D thermo-fluid-dynamic analysis was used to reproduce the volumetric losses. Three main leakages paths are considered: the leakages trough the gap between the blades tip and stator inner surface (element f), between the blades side and rotor slot (element g) and between the rotor face and machine casing (element h). The (f) and (g) leakages are treated through the Poiseuille-Couette equation whereas (h) is assessed thanks to the equivalent orifice approach [11, 12]. Leakages, however, influence the pressure angular (or volume V_i) trend inside the chamber p_i during rotation (time t_{cycle}) and consequently the indicated power P_{ind} (1). Once the indicated power was evaluated, the net expander power P_{exp} can be achieved subtracting the mechanical losses P_{losses} due to friction. The mechanical power losses are physically represented in SVRE model following a 0-D approach. All the mechanical losses source has been considered through subroutines reported in the element (l). Anyway, the power lost due to the dry contact between blades tip and stator inner surface represents the 95% of all mechanical losses. This contribution is evaluated according to Eq. (2) where f is the friction factor, r_v is the distance between the blade tip and rotor centre and ω the expander speed.

It is worth to mention that in (2) F_c represents the centrifugal force pushing the blade against the stator inner surface whereas F_p is the pressure force that that fluid

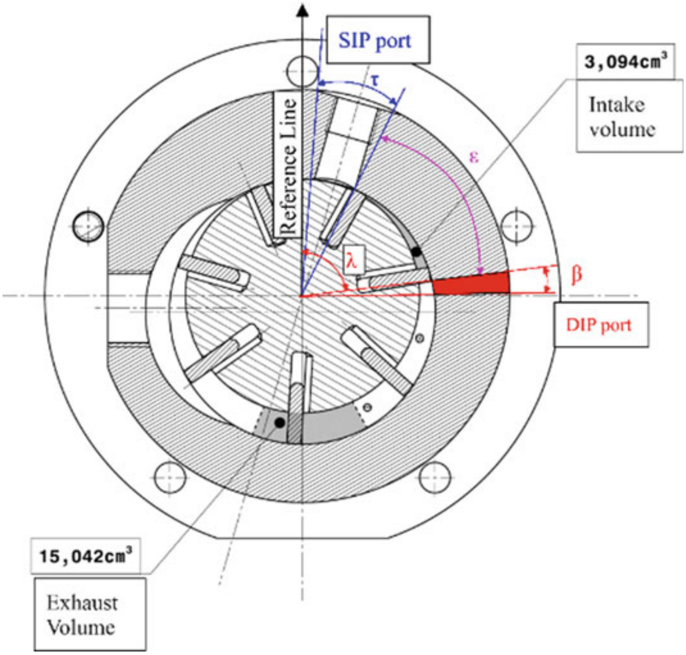
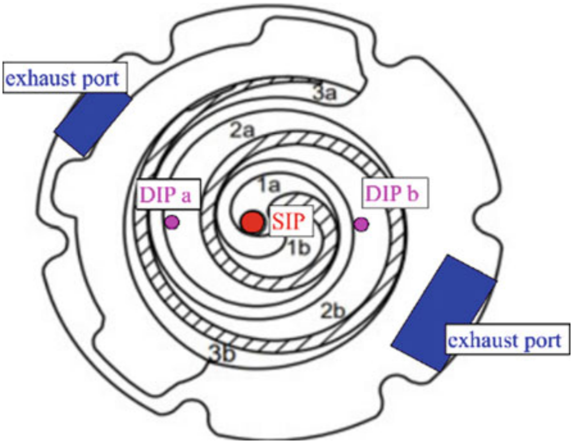


Fig. 3 Sliding Rotary Vane expander

Fig. 4 Scroll expander



enclosed under the blades exerts. Once the mechanical power is known, the expander efficiency can be evaluated as the ratio between P_{exp} and reference power P_{ad}, is that produced by the expander if the expansion is adiabatic isentropic. The ratio between mass flow rate $\dot{m}_{WF}$ and the inlet/outlet expander pressure difference Δp_{exp} defines the machines permeability α (3). Similarly to the SVRE, also the scroll theoretical model

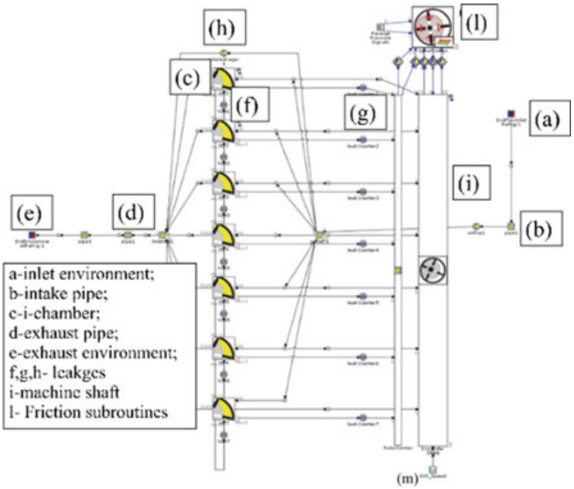


Fig. 5 SVRE theroetical model

was developed in GT-Suite™ environment following the same procedure with some difference due to the more complex geometry (Fig. 4). The fixed and orbiting scrolls define six chambers. The intake phase happens axially filling chambers when are in 1a and 1b positions. The intake phase ends after a complete rotation. After the intake phase, the chambers branch off and are in correspondence of 2a and 2b positions. As the expansion going on the chambers proceeds towards position 3a and 3b in correspondence to which the exhaust phase takes place. Therefore, such behaviour suggests a symmetric structure for the model as reported in [13]. Concerning the mechanical power losses modelling it was considered according to a map of the mechanical efficiency following the approach of [13]. Both the models were validated against experimental data. Concerning SVRE, the experimental analysis was carried out for different values of mass flow rate provided by the pump which varies from 56 g/s up to 74 g/s. In order to keep the expander intake pressure close to the design value, the revolution speed was properly increased between 1245 and 1770 RPM following the $\dot{m}_{WF}$ growth [14]. Such approach ensures intake pressure varies in a narrow range (9.5–10.5 bar) despite the mass flow rate increase. Hence, the expander works close to the design conditions thus producing a P_{exp} ranging from 608 W up to 716 W. The comparison of these experimental data with the corresponding theoretical predictions shows a good agreement. Indeed, maximum relative errors in terms of expander intake pressure and power produced are equal to 5% and 8% respectively. A similar validation approach was carried out for the scroll expander.

$$P_{ind} = \frac{\sum_{i=1}^{N_v} \oint p_i \mathrm{d}V_i}{t_{cycle}} \tag{1}$$

$$P_{losses} = f N_v \left(F_c + F_p\right) r_v \omega \tag{2}$$

$$\alpha = \frac{\Delta_{WF}}{\Delta p_{exp}} \tag{3}$$

In this case, despite the expander speed is not controlled, the expander intake pressure linearly grows from 7.6 bar up to 10.7 bar when the mass flow rate varies from 32 g/s up to 54 g/s thus increasing the produced power from 398 W up to 545 W with mass flow rate enhancement. This is since the permeability α (3) can be retained constant (0.06 kg MPa^{-1} s^{-1}) [14]. Also this case, the model can reproduce the experimental behaviour as demonstrated by the low maximum relative errors in terms of expander intake pressure (7%) and produced power (10%).

3 Results

Once the SVRP and Scroll model were validated, they were used to assess the benefits introduced by DIP in the two cases. The introduction of DIP involves a slight modification of the machine and consequently of the model. Indeed, as observed in Figs. 3 and 4 the geometry remains the same. For SVRE case (Fig. 3) the only difference is that a further intake port is done angularly spaced from the main intake one (SIP) in the sense of the rotation. The DIP was introduced in correspondence of the expansion as it can be observed from Fig. 3. This position indeed allows to achieve a best compromise between the power produced and the machine efficiency [11]. As it can be observed in Fig. 2, the DIP port opening angle λ is equal to 91°, measured with respect to the reference line. Hence, considering that the distance of SIP port closing angle from the reference line τ is equal to 37°, the angle difference ε is 54°. Considering that DIP port presents an angular extent of 6°, the phase of the DIP presents an angular duration of 60°. The introduction of DIP technology port in also in the case of Scroll involves slight modifications (Fig. 4). Indeed, the only variation is the introduction of two symmetric ports. This is performed according to the approach developed in [13]. In fact, it was observed as the Scroll structure leads to pair of chambers (1a and 1b, 2a and 2b, 3a and 3b) whose volume symmetrically varies during rotation. Hence, two symmetric DIP technology ports should be introduced to avoid disequilibrium in the machine filling. The DIP technology can be done in a Scroll expander just introducing the ports on the fixed orbiting scroll as observed in Fig. 4. So, no adduction pipes are required being the intake phase axial and performed through the same intake manifold. As it was demonstrated in [13], the DIP technology should present a diameter lower than the spiral thickness to prevent that the DIP technology feeds simultaneously two consecutive chambers (i.e. 2a and 3a) in the sense of the expansion. Hence, the spiral thickness (3.5 mm) is equal to the maximum DIP diameter Φ. In the analysis also a lower Φ is considered (1.5 mm) to observe its impact on DIP Scroll performance. For the considered scroll expander, a rotation of 996° is needed to complete the whole cycle. After 360° the intake phase was completed. Subsequently, the expansion phase takes place up to 720° and finally the discharge phase happens. The DIP reported in Fig. 4 were installed to keep the machine filling even during the expansion phase. So, the DIP starts at 360° (after the SIP phase) and ends at 720°. Hence, in both SVRE and Scroll cases, the aim of DIP is to delay the pressure reduction during the expansion thus increasing the indicated power and consequently the mechanical power. This is achieved introducing a further amount of working fluid during the expansion phase. Hence, the extra mass flow rate elaborated by the expander produces a pressure boosting with the increase of the area of indicated cycle. Such effects can be observed for SVRE in Fig. 6a by the comparison between SIP and DIP indicated cycle. Figure 6a clearly shows as in correspondence of the DIP intake opening angle the pressure increases despite the chamber volume is growing. Such action delays the pressure reduction with respect to the SIP machine. In this way an increase of the area of the indicated cycle (1) was achieved. The indicated cycle area represents the power exchanged by the working fluid and the machine components, so DIP ensures an increase of power produced by the machine as it can be observed in Fig. 6b. The power benefit is significant for all the operating range considered. Indeed, increasing the pressure difference at the expander side from 4 bar up to 13 bar, the power enhancement decreases from 150% up to 77%. This power increase is due to the higher mass flow rate elaborated by the machine (+86%) as it can be noticed from Fig. 6c. This result shows a permeability increase of DIP SVRE. So, keeping constant Δp_{exp}, it can be observed as DIP machine allows to elaborate a higher mass flow rate. In fact, the permeability of DIP SVRE is equal to 0.11 kgs^{-1} MPa^{-1} at 1500 RPM whereas it is 0.09 kgs^{-1} MPa^{-1} in SIP case at the same speed. DIP technology allows also to introduce efficiency benefits demonstrating that the power increase is not simply related to a higher mass flow rate elaborated by the expander. This can be observed, in Fig. 6c where the two efficiencies of the DIP and SIP technologies are compared. DIP SVRE efficiencies varies from 50% up to 40% for a Δp_{exp}, ranging between 4 and 10 bar. In the same interval, the SVRE presents a maximum value of 40%. The SIP allows to achieve a slightly higher efficiency (+4%) only for pressure rise higher than 10 bar. This is since the efficiency of the DIP SVRE presents a higher reduction with Δp_{exp}, than SIP case which shows a flatter curve. Anyway, in this point the DIP SVRE produces a 77% higher power so the benefits of DIP machine still apply.

It is worth to mention that the introduction of a DIP (Fig. 7a) is different from the case of a SIP with an extended port (and greater intake volume), Fig. 7b. DIP technology avoids that multiple chambers would be opened toward the main intake port (as it happens when an extended SIP is done) preventing that the pressure, and consequently the power (Fig. 7c), decreases too much when lower mass flow rates are aspirated by the machine. Hence the adoption of a greater intake volume—Fig. 7b—shifts the operating region to higher mass flow rate which are suitable to completely fill the intake volume whereas the adoption of a DIP solution allows to manage in a similar way the higher flow rates but also the situations of lower flow rates avoiding the decrease of the pressure inside chambers. The operating region of the machine is, therefore, widened. DIP in Scroll expander produces the same phenomenological effect on the indicated cycle of the SVRE case (Fig. 8a). Nevertheless, the pressure boosting is significant only for the case of Φ equals 3.5 mm. This behaviour is

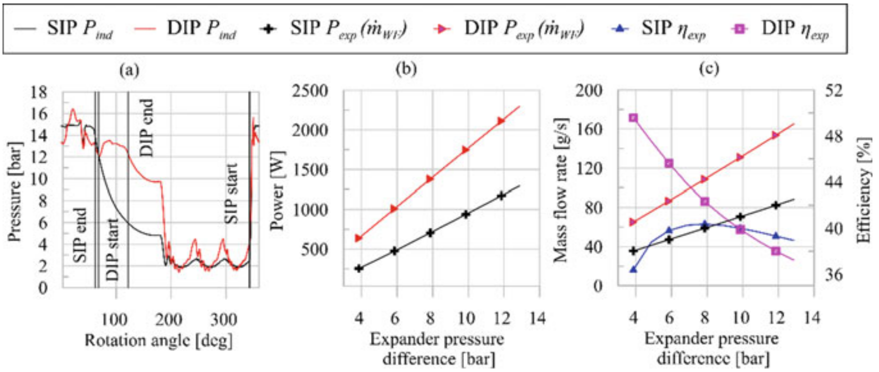


Fig. 6 Indicated cycles **a**, power **b**, mass flow rate and efficiency **c** as function of expander pressure difference for SIP and DIP SVRE technology expander

reflected on the power increase as Fig. 8b shows. In fact, for Φ equal to 1.5 mm the power increase is slight. It ranges from 8% up to 1% when the Δp_{exp} varies from 4 up to 11 bar. After 11 bar, the DIP technology produces a power decrease with respect SIP solution (−0.5%). If the DIP technology with Φ of 3.5 mm is considered, the power boosting is higher but also in this case it applies until to a Δp_{exp} equal to 11 bar is reached. Indeed, in the same Δp_{exp} range the power increase diminishes from 27 to 2%. After 11 bar, with DIP solution a power decrease up to 17% is observed. Such results confirm that despite the effects of DIP technology introduction is the same for both expanders the benefits on the two machines are different. For SVRE the power boosting is significant, and it applies for all Δp_{exp} which results from different flow rates crossing the first and the second port. In the case of scroll expanders, the power increase is reduced (but it is still present) and it applies only for a limited Δp_{exp} range.

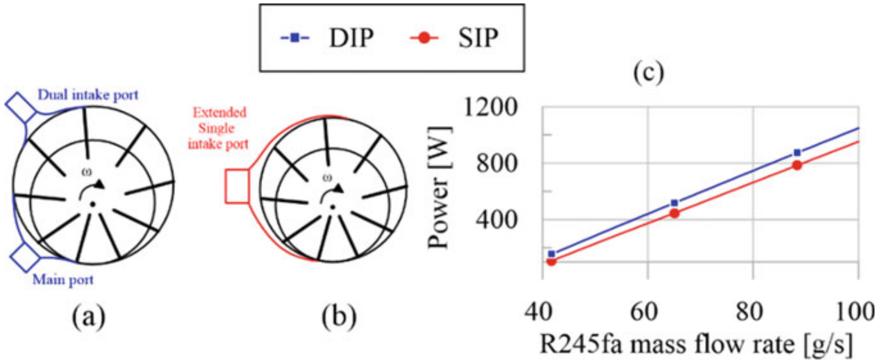


Fig. 7 DIP **a** and extended SIP **b** configurations and produced power comparison **c**

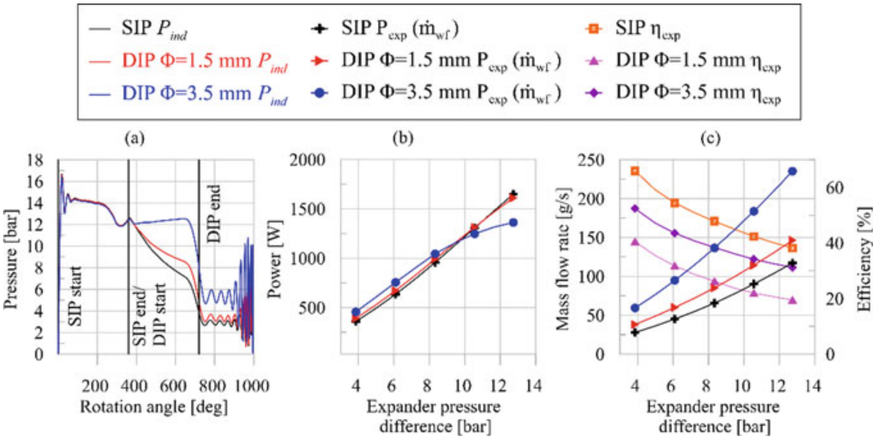


Fig. 8 Indicated cycles **a**, power **b**, mass flow rate and efficiency **c** as function of expander pressure difference for SIP and DIP Scroll technology expander

This is because in SVRE the further mass flow rate sucked through second port plays a more effective role due the lower volume in which is introduced. Indeed, for SVRE, the volume during which the second port is opened varies from 3.79 cm^3 till to 10 cm^3; In the scroll case, the second port feeds the corresponding scroll chamber when the volume varies from 6 cm^3 up to 11 cm^3. Also DIP Scroll expander can elaborate more mass flow rate than SIP one keeping constant Δp_{exp} (Fig. 8c). The flow rate increases when Φ of second port grows. Indeed, permeability raises from 0.06 kgs^{-1} MPa^{-1} of the SIP technology case up to 0.11 kgs^{-1} MPa^{-1} and 0.16 kgs^{-1} MPa^{-1} respectively when Φ is 1.5 mm and 3.5 mm. Nevertheless, this permeability increase provides lower benefits on power boosting as the extra mass flow rate is introduced in a larger volume and the effect on the pressure inside the chamber is reduced (Fig. 8a). It appears clear that if the diameter of the port could have been larger, the effect on power would have been greater as a larger flow rate was introduced to increase the pressure until to the main intake value. Hence, being the power boosting weak, the extra mass flow rate leads to an efficiency decrease for DIP technology solution as observed in Fig. 8c. Here, it can be seen how the SIP solution presents a higher efficiency varying from 70% up to 40% for a Δp_{exp} ranging from 4 bar up to 13 bar. When DIP is considered, the efficiency decreases from 53% up to 30% and from 40% up to 20% in the same operating range. So, the Scroll expander produces more power but its efficiency is lower. This result is due to the higher volume of Scroll machine when DIP feeds the machine. So, a reduction of this volume through an optimization of machine spirals could allows to overcome this issue. For both SVRE and SVRE cases, the adoption of DIP ensures to reduce the pressure difference among two adjacent chambers [15], with respect to the more conventional SIP machine. This provides a reduction of the ratio between the leakages flow and the elaborated mass flow rate by the machine. From a quantitative point of view, from 5.8% up to 4.6% and for 0.08% up to 0.06% respectively for SVRE and Scroll expander.

4 Conclusion

In the present paper the benefits introduced by the introduction of DIP technology for a Sliding Rotary Vane and Scroll Expander were assessed when they are operated in a small-scale ORC-based power unit. Thanks to the experimental characterization carried out on both expanders, theoretical models of the two machines were built and validated. The results show the same fluid-dynamic behaviour of the two machines when DIP technology is introduced. In both expanders, the DIP technology introduction provides a permeability increase causing, for the same pressure difference at the expander side, an aspiration of a higher mass flow rate thus boosting the pressure inside the vanes, increasing indicated work. DIP SVRE elaborate up to 84% of mass flow rate which allows to increase the power up to 150% than the original SIP expander. Benefits are observed also for the machine efficiency for a wide operating range where the DIP efficiencies range from 50% up to 38% and the SIP ones between 36 and 40%. DIP introduction provides a permeability increase also when it was applied to scroll expanders. In fact, for the same inlet/outlet expander pressure, the mass flow rate elaborated by the machine grows up to 30% and 100% according to the dimension of the circular port (1.5 mm and 3.5 mm respectively). So, the produced power increases up to 8% and 27% respectively with a DIP port equal to 1.5 mm and 3.5 mm. This reduced effect on power with respect to SVRE is due to the higher chamber volume than SVRE when DIP ports feed the machine thus limiting the pressure boosting inside the chamber. To overcome this issue, the geometry of the spiral can be modified to reduce the volume of the chamber fed by the DIP port.

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References

1. M.A. Chatzopoulou, S. Lecompte, M. De Paepe, C.N. Markides, Off-design optimisation of organic Rankine cycle (ORC) engines with different heat exchangers and volumetric expanders in waste heat recovery applications. Appl. Energ. **253**, 0306–2619 (2019)
2. M.A. Ancona, M. Bianchi, L. Branchini, A. De Pascale, F. Melino, A. Peretto, C. Poletto, N. Torricelli, Solar driven micro-ORC system assessment for residential application. Renew. Energ. **195**, 167–181 (2022)
3. J. Song, Y. Wang, K. Wang, J. Wang, C.N. Markides, Combined supercritical CO_2 (SCO_2) cycle and organic Rankine cycle (ORC) system for hybrid solar and geothermal power generation: thermoeconomic assessment of various configurations. Renew. Energ. **174** (2021)

4. K. Braimakis, A. Charalampidis, S. Karellas, Techno-economic assessment of a small-scale biomass ORC-CHP for district heating. Energ. Convers. Manage. **247**, 114705 (2021)
5. M. Manfredi, A. Spinelli, M. Astolfi, Definition of a general performance map for single stage radial inflow turbines and analysis of the impact of expander performance on the optimal ORC design in on-board waste heat recovery applications. Appl. Therm. Eng. **224**, 119857 (2023)
6. C. Mateu-Royo, A. Mota-Babiloni, J. Navarro-Esbrí, B. Peris, F. Molés, M. Amat-Albuixech, Multi-objective optimization of a novel reversible High-Temperature Heat Pump-Organic Rankine Cycle (HTHP-ORC) for industrial low-grade waste heat recovery. Energ. Convers. Manage. **197**, 111908 (2019)
7. O. Dumont, A. Parthoens, R. Dickes, V. Lemort, Experimental investigation and optimal performance assessment of four volumetric expanders (scroll, screw, piston and roots) tested in a small-scale organic Rankine cycle system. Energy **165**(Part A) (2018)
8. J. Bao, L. Zhao, A review of working fluid and expander selections for organic Rankine cycle. Renew. Sustain. Energ. Rev. **24**, 325–342 (2013)
9. A. Kovacevic, N. Stosic, I.K. Smith, E. Mujic, Advances in numerical modelling of helical screw machines (2010)
10. M. Bianchi, L. Branchini, N. Casari, A. De Pascale, F. Melino, S. Ottaviano, M. Pinelli, P.R. Spina, A. Suman, Experimental analysis of a micro-ORC driven by piston expander for low-grade heat recovery. Appl. Therm. Eng. **148**, 1278–1291 (2019)
11. F. Fatigati, M. Di Bartolomeo, R. Cipollone, Dual intake rotary vane expander technology: experimental and theoretical assessment. Energ. Convers. Manage. **186**(156–167), 0196–8904 (2019)
12. F. Fatigati, M. Di Bartolomeo, D. Di Battista, R. Cipollone, A dual-intake-port technology as a design option for a Sliding Vane Rotary Expander of small-scale ORC-based power units. Energ. Convers. Manage. **209**(112646), 0196–8904 (2020)
13. F. Fatigati, G. Di Giovine, R. Cipollone, Feasibility assessment of a dual intake-port scroll expander operating in an ORC-based power unit. Energies **15**, 770 (2022)
14. F. Fatigati, D. Vittorini, A. Coletta, R. Cipollone, Assessment of the differential impact of scroll and sliding vane rotary expander permeability on the energy performance of a small-scale solar-ORC unit. Energ. Convers. Manage. **269**, 116169 (2022). ISSN 0196-8904
15. F. Fatigati, M. Di Bartolomeo, R. Cipollone, On the effects of leakages in Sliding Rotary Vane Expanders. Energy **192**, 116721 (2020). ISSN 0360-5442