Feasibility of Boosting Low-Energy-Quality Steam by Using Wave Rotor

Yuqiang Dai¹,²,a*, Zhipeng Tang¹, Mohan Li¹, Gang Hao²,³, Luwei Zhang¹ and Jintao Wu¹,²,b*

¹Department of Chemical Machinery and Safety Engineering, Dalian University of Technology, Faculty of Chemical Engineering, room H515, Chemical Experiment Building, Dalian, Liaoning, China.
²Special Fluid Technology and Equipment Joint Research and Development Centre of Dalian University of Technology and Ackam (Jiangsu) Industrial Technology Co., Ltd. China.
³Ackam (Jiangsu) Industrial Technology Co., Ltd., No.280 Fumin Road, Economic development zone, Changzhou, Jiangsu, China.
Email: ¹daiyuqiang@dlut.edu.cn, ²wuji75@dlut.edu.cn

Abstract. Owing to the difficult utilization of the low-pressure level in the process industry, the low-energy-quality steam is often condensed to recover the demineralized water or just discharged directly, causing a huge waste of thermal energy. A novel technology of enhancing the steam’s energy quality by using the wave rotor based on the principle of moving shockwave compression is proposed. The supercharging ability of 3-port wave rotor is studied by meaning of 1-dimension unsteady theory and computational fluid dynamic. A practical thermodynamic flowsheet of boosting the low-pressure steam driven by high-pressure steam is also proposed and analysed in detail. As an example, to boost the saturated steam of pressure 1.0 MPa to 1.953 MPa, a three-stage wave rotor solution is proposed and is verified its feasibility. The high supercharging ratio and entrainment ratio of the wave rotor are much higher than the traditional steam ejector shows the feasibility of enhancing energy-quality of low-pressure steam.

Keywords. Steam boosting, shockwave, wave rotor, work exchanging network.

1. Introduction
Steam is an important part of utilities in process industries such as petroleum, chemical and energy. Energy power cost accounts for a large proportion of the total cost of production and is an important part of the price of products. It has always been the focus of energy conservation and emission reduction in factories. The energy quality of industrial steam is determined by the pressure level. The high pressure or high energy quality steam can be used flexibly in the process equipment. However, the-state-of-the-art situation is that after the integrated optimization of the process equipment’s energy, a large amount of saturated steam by-products with the pressure level of one bar will be obtained. Their energy quality is low and often cannot be effectively utilized. Finally, low-energy-quality steam will be discharged or recycled to softened water by the external condenser, so lots of low-quality energy is often wasted.

Low-quality steam energy recycling has become an important issue for energy saving in various process industries. However, surveys of domestic and international research have found that typical
solutions use the remaining heat to recycle condensed soft water and use superheaters to turn steam into superheated steam. The main technical disadvantage in such heat transfer technology of steam energy utilization is that the total heat transfer factor between superheated vapour and process stream is always very low, and the heat exchanger has very large volume or large investment.

The solution aiming at improving low-quality steam pressure is a natural choice. The conventional method uses a compressor to boost the steam to the desired high pressure. The technology also has economic and technical problems. On the one hand, electric energy has higher quality, so it is not an ideal choice to consume it. On the other hand, due to the low viscosity of steam and the large specific capacity, it is difficult to maintain the boundary layer of centrifugal steam compressor blades. It is hard for engineers to develop such a high-speed centrifugal compressor with a large volume flow rate.

In this article, a novel idea that uses moving shock waves to supercharge the low-quality steam to increase its energy quality, is proposed. The steam after enhancing quality can be used as process utility in equipment again. This low-energy-quality improving technology based on shock wave supercharging principle will become the key technology in energy conservation of process industry.

2. Gas-dynamic and Thermodynamic Model of Wave Rotor

2.1. Gas Dynamic Model of Wave Rotor

The shock boosting process is implemented in an advice called wave rotor which is an unsteady flow device where two streams exchange pressure energy directly due to movement of gas waves generated in channels [1]. It can get higher isentropic process efficiency than steady flow devices like diffusers [2-3]. Strong and weak discontinuities such as moving shock wave $S$, entropy waves (including rarefaction wave $E$ and compression wave $C$) and contact face $J$ are formed in wave rotor channels by using a series of circumferentially evenly arranged, double-ended open-ended shock wave tubes under periodic discontinuous boundaries (periodic on/off of inlet and outlet ports) to complete the shock wave supercharging and rarefaction wave self-cooling processes which is different from the steady expansion and compression processes of turbine technology. It is the unsteady moving shock supercharging and rarefaction wave expansion processes.

Wave rotors complete directly pressure energy exchange by gas wave which is different from kinetic energy transfer of turbine technology. This energy transfer pathway of the wave rotor is short (without kinetic energy transfer) and quick (at level of the sonic speed) [4]. Therefore, the rotors can be designed at a low revolution speed. It solves the problem of kinetic energy loss caused by high rotation speed and liquid hammer of turbine technology. And the structure of the bilateral opened channel of the wave rotor’s drum makes the liquid drainage convenient and is suitable for operation with wet steam.

Both turbine technology and the wave rotor are the key technologies for efficient use of pressure, they can achieve compression with high expansion refrigeration efficiency. However, the supercharging expansion process of moving gas wave is efficient, and its application can reduce the volume of the equipment significantly due to its unsteady characteristics [5]. These are the fundamental reasons why the powerful nations of science and technology have tried to apply this kind of mechanical development to various fields.

The port number of the wave rotor can be three, and the working wave diagram is shown in figure 1. The through-flow (TF) type of such a wave rotor has the topical characteristics as follows:

- It can fully utilize the self-cooling characteristic of the periodic motion rarefaction wave to cool the channel and achieve a relatively small temperature rise when supercharging [6]. It undergoes multiple rarefaction wave expansion and shock wave compression in one working cycle at a certain axial position in the rotor channel.
- There are two advantages for unchanged direction of the steam velocity in the channel: Firstly, it is easy to discharge from the right port when there is liquid in the rotor channels. Secondly, both hot and cold streams flow through the channel from the left to the right, causing great reduction of the axial heat conduction of the channel wall, and reduction of the heat loss.
Figure 1. The typical working wave diagram of a three-port wave rotor supercharger.

Figure 2. Wave diagrams illustrated by pressure (a) and temperature (b) in shocktubes.

Table 1. The results of the steam shock tube with \( p_4 = 2.5 \text{MPa} \) and \( p_1 = 0.5 \text{MPa} \).

| Zone No. | Pressure /kPa | Temperature /K | Enthalpy /(kJ.kg\(^{-1}\)) | Velocity /(m.s\(^{-1}\)) |
|----------|---------------|----------------|-----------------------------|--------------------------|
| 1        | 500.00        | 426.15         | 2750.92                     | 494.81                   |
| 2        | 1126.69       | 520.67         | 2932.80                     | 547.01                   |
| 3        | 1126.69       | 458.28         | 2649.73                     | NaN\(^a\)                |
| 4        | 2500.00       | 497.15         | 2802.10                     | 504.73                   |

\(^a\) Vapor-liquid two phase exists.

The supercharging capacity of the wave rotor can be estimated by gas dynamics methods. A feasible way to evaluate the supercharging performance of the moving shockwave is to use the shock tube, where there is a high pressure zone \( 4 \) separated with the low pressure zone \( 1 \) by a diaphragm at \( t=0.0 \text{s} \). Table 1 shows the typical results of the supercharging ability of the moving shockwave with \( p_4 = 2.5 \text{MPa} \) and \( p_1 = 0.5 \text{MPa} \) in the shocktube filled with saturated steam on both sides of the diaphragm. The maximum theoretical pressure of the incident shock is about 1.1MPa, or the pressure ratio of the incident shock is \( p_{21} = p_2/p_1 = 2.2 \). These results can be verified by the computational fluid dynamics (CFD), and the wave diagram is shown in figure 2.

2.2. Thermodynamic Model of Wave Rotor

According to the wave rotor working wave diagram (figure 1), both driving high pressure steam and the driven low-energy-grade steam experience multiple times shockwave compression and rarefaction wave expansion processes. The driving side experiences 4 expansion and 1 compression processes crossing the zones of HP port → (VI) → (VII) → (VIII) → (IX) → (X) → MP port in \( x-t \) diagram, the driven side experiences 1 expansion and 2 compression processes crossing the zones of LP port→ (I) → (II)→ (III) →(IV) → (V)→ MP port. It follows that the expansion side (driving fluid side) and the compression side (driven fluid side) of the wave rotor are separated by the contact surface \( J \) which is just like a massless piston. Theoretically, the driving and driven fluids have no mass transfer, and the energy exchange between them is directly transmitted through the volumetric work \( w = -p_d v \), if reversible. It is completely different from the velocity-type transfer shaft work way of the expansion-compression process of turbine and is a thermodynamic process without shaft loss. According to the
unique energy transfer principle, a single thermodynamic model of the wave rotor can be established, as shown in figure 3.

![Figure 3. The thermodynamic model of wave rotor.](image)

As the model shown in figure 3, because of the unsteady working process of the expansion work and compression work, the efficiency of wave rotor is always higher than that of the turbomachine. The thermodynamic model of wave rotor can also be modelled with the compression isentropic efficiency $\varepsilon_{\text{com}}$ and expansion isentropic efficiency $\varepsilon_{\text{exp}}$ [7-8]. At the same time, there are many leakage paths [9] at the driving or driven side in the wave rotor. All these leakage processes can be regarded as throttling processes. Besides, the driving and driven streams inevitably have the mixing and thermal diffusion phenomena caused by the distortion of the contact face in the practical working process [10-11]. Especially, for 3-port wave rotor, the driving and driven streams will mix in the MP port and have the mixing loss. All these mixing losses are also included in the factors of $\varepsilon_{\text{com}}$ and $\varepsilon_{\text{exp}}$.

3. The Feasibility of Application Examples of Stream Supercharging Technology

Based on the boosting characteristic and the thermodynamic model of wave rotor, it is convenient for engineers to analyse a special process system, such as the automated-cascaded refrigeration cycle with wave rotor, the multiple effect evaporation system with gasdynamic wave vapour recompression, and so on. The following provides a novel solution to enhance the steam energy quality in the process industry. For example, steam with a flow rate of 7.1tms/h can be supercharged from 1.0 MPa to 1.953 MPa by using the wave rotor. The process flowsheet diaphragm (PFD) of such a system can be modelled as shown in figure 4.

![Figure 4. A practical flowsheet of boosting low-pressure steam by using wave rotor.](image)

Accounts for the-stage-of-the-art wave rotor boosting technology, to get about the boost pressure ratio 2.0, one can use three stages of wave rotors with the entrainment ratio of about 0.30. The mass flowrates, entrainment ratio (ER), and pressure ratio (PR) of each stage of the wave rotors are shown...
in table 2. The $PR$ of the first stage is $PR_1=1.25\text{MPa}/1.0\text{MPa}=1.25$, it will consume 22.19 tons/h superheated driving steam with the pressure of 1.953MPa, which is part of the output of a 3-stage wave rotor rig. The $PR_2=1.563\text{MPa}/1.25\text{MPa}=1.25$ at the second stage, the 2.441 MPa, 225.3 ℃ slightly superheated steam with the flow rate of 97.65 tons/h is needed. The final supercharged steam of 1.953 MPa is slightly over-heated with 222.1 ℃. In the first stage, the wave rotor can accomplish the process with $\epsilon_{exp} > 44.73\%$, and $\epsilon_{com} > 60.0\%$; in the second stage, the isentropic efficiencies must be $\epsilon_{exp} > 44.34\%$ and $\epsilon_{com} > 60.0\%$, and in the third stage, the isentropic efficiencies must be $\epsilon_{exp} > 46.13\%$ and $\epsilon_{com} > 70.0\%$.

Table 2. The mass flowrate of driving (HP), driven (LP) and supercharged (MP) streams of the wave rotor.

|       | HP port | LP port | MP port | PR   | $ER_s$ |
|-------|---------|---------|---------|------|--------|
| 1st stage | 22.19   | 7.10    | 29.29   | 1.25 | 0.32/0.32 $^{a}$ |
| 2nd stage | 97.65   | 29.29   | 126.94  | 1.25 | 0.30/0.33 $^{a}$ |
| 3rd stage | 426.10  | 126.94  | 550.14  | 1.25 | 0.30/0.37 $^{b}$ |
| 4th stage | 1760.00 | 527.90  | 2288.00 | 1.25 | 0.30/0.27 $^{b}$ |

$^a$ The CFD results of optimal structure.
$^b$ No CFD is available, so we give the in-house-code results.

Figure 5. A practical industrial flowsheet of temperature and pressure reduction rig by using check valve set.

For contrast, the conventional steam ejector is also analysed at the same pressure and temperature boundary conditions. For getting the same $PR=1.25$, at the same inlet process parameters, the first stage of the ejector has negative entrainment ratio. It follows that at a low expansion ratio, the boost performance of ejectors is much lower than that of the wave rotor. Therefore, the wave rotor can achieve a larger $ER$ under the same $PR$, and it means more driven steam can be supercharged by using wave rotor. Figure 5 shows a practical industrial flowsheet of temperature and pressure reduction rig by using a check valve set. With the same driving steam of 2.8 MPa and 240 ℃, we want to get the same object steam of 1.953 MPa and 222.1 ℃. By the temperature and pressure reduction technology, only 0.864 tons/h additional steam is produced, which is much lower than the wave rotor boosting technology (7.1 tons/h).

4. Conclusion

Different from the working principle and energy conversion mode of turbine technology, wave rotor technology can realize unsteady shock supercharging and rarefaction wave expansion processes and direct energy exchange between driving steam and driven steam, and has a high energy conversion efficiency and compact size. Based on the thermodynamic model of the wave rotor, a novel solution to enhance the quality of low-energy steam is proposed and verified its feasibility by a typical case in process industry. It is a promising technology to use the wave rotor to exchange the work between the high-pressure steam and low-pressure-steam and will be widely used in work exchanger network [12] optimal integration system.
Acknowledgments
This present work is supported by the National Key Research and Development Program of China (2018YFA0704602), and the National Natural Science Foundation of China projects (51476015 51106017).

References
[1] Dai Y Q, Ding M X, Tan W H and Hu D P 2010 *J. Dalian Univ. Technol.* **50** 888-895
[2] Akbari P, Nalim R and Mueller N 2006 *J. Eng. Gas. Turb. Power*, **128** 717-735
[3] Akbari P, Kharazi A A and Müller N 2003 *Proc. of the ASME 2003 Inter. Mechanical Engineering Congress* IMECE2003-55222 p 1
[4] Weber H E 1986 *ASME 1986 Inter. Gas Turbine Conf. and Exhibit (Dusseldorf)* 86-GT-62 1 p V001T01A025
[5] Piechna J, Akbari P, Iancu F and Müller N 2004 *Proc. of IMECE04 2004 ASME Inter. Mechanical Engineering Congress (Anaheim)* IMECE2004-59022 p 1
[6] Fatsi A and Ribaud Y 1999 *Aerosp. Sci. Technol.* **3** 293-299
[7] Chan S N, Liu H X and Xing F 2016 *J. Eng. Gas Turb. Power* **138** 112601
[8] Dai Y Q, Zou J P, Zhu C, Liu P Q, Zhao J Q, Zhang L M and Hu D P 2010 *J. Therm. Sci.*, **2** 021011
[9] Akbari P, Nalim R, Donovan E S and Snyder P H 2008 *J. Propuls. Power*, **24** 732-740
[10] Dai Y Q, Liu F X, Wu J T, Wei W, Hu D P Liu X W 2013 *Proc. of the ASME 2013 Inter. Mechanical Engineering Congress and Exposition (San Diego)* IMECE2013-63449 p 1
[11] Hu D, Li R, Liu P, Zhao J 2016 *Int. J. Heat Mass Transf.* **100** 497-507
[12] Razib M S, Hasan M M F and Karimi I A 2011 *Comput. Chem. Eng.* **37** 262-277