Characteristics of Working Fluid Flow in Convergent-Divergent Injectors in Vapor Compression – Steam Jet Refrigeration

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Characteristics of Working Fluid Flow in Convergent-Divergent Injectors in Vapor Compression – Steam Jet Refrigeration

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Abstract: The vapor compression refrigeration-steam jet refrigeration system (VCR-SJR) is one of the technological innovations that have been widely applied. Vapor compression refrigeration (VCR) and steam jet refrigeration (SJR) are connected by an intercooler. The VCR unit uses the Hydrocarbon MC 22 refrigerant working fluid. The vacuum process in the SJR unit is provided by a convergent-divergent type injector. The performance of the VCR-SJR refrigeration engine is influenced by the characteristics of the working fluid flow in the injector. The technological innovation of this research is the combined VCR-SJR refrigeration machine using a convergent-divergent type injector in the SJR unit and the VCR unit using MC 22 refrigerant. This study aims to determine the characteristics of the working fluid flow in the injector of the VCR-SJR refrigeration machine. The characteristics are the working fluid flow and pressure profiles in the convergent-divergent injector with variations in the suction injector diameter. Visual fluid flow analysis in convergent-divergent injectors is performed by simulation using ANSYS 16.0 with a FLUENT system analysis feature. Validation is carried out by testing an injector that has the following dimensions: suction chamber diameter 28 mm, nozzle inlet diameter 14 mm, suction chamber length 58 mm, secondary fluid inlet diameter (10, 15, and 20 mm), nozzle outlet diameter 5 mm, mixing chamber length 130 mm, throat length 95 mm, diffuser length 130 mm, and injector outlet side diameter 40 mm. It is concluded that the suction side diameter affects the working fluid flow profile in the injector.

Keywords: refrigeration, vapor compression, steam jet, working fluid, injector.

蒸汽压缩-蒸汽喷射制冷中会聚-发散喷射器工作流体流动特性

摘要：蒸汽压缩式制冷-蒸汽喷射式制冷系统（录像机-SJR）是已被广泛应用的技术创新之一。蒸汽压缩制冷 (录像机) 和蒸汽喷射制冷 (SJR) 通过中间冷却器连接。录像机装置使用碳氢化合物 MC 22 制冷剂工作流体。SJR 单元中的真空过程由收敛-发散型喷射器提供。录像机-SJR 制冷发动机的性能受喷射器中工作流体流动特性的影响。本研究的技术创新是在 SJR 机组和录像机机组采用 MC 22 制冷剂的集散型喷射器的录像机-SJR 组合制冷机。本研究旨在确定录像机-SJR 制冷机喷射器中工作流体的流动特性。特征是收敛-扩张喷射器中的工作流体流量和压力分布，其中吸入喷射器直径发生变化。采用具有流利系统分析功能的 ANSYS 16.0 进行仿真，对收敛-发散喷射器中的流体流动进行可视化分析。通过测试具有以下尺寸的喷射器进行验证：吸入室直径 28 毫米，喷嘴入口直径 14 毫米，吸入室长度 58 毫米，二次流体入口直径（10、15 和 20 毫米），喷嘴出口直径 5 毫米，混合室长度 130 毫米，喉部长度 95 毫米，扩散器长度 130 毫米，喷射器出口侧直径 40 毫米。得出结论，吸入侧直径影响喷射器中的工作流体流动分布。

关键词: 制冷、蒸汽压缩、蒸汽喷射、工作流体、喷射器。

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1. Introduction

Along with the rapid development of the industry, energy consumption is increasing as well. On the other hand, the world's energy reserves, especially fuel oil, are depleting and gradually run out. Therefore, strategic steps and innovation are needed to obtain energy-efficient technology. Applying a combined heat and power (CHP) system is very appropriate for industries that require a power plant and a cooling system. Steam jet refrigeration (SJR) is one of the technologies applied in the food industry sector. The SJR system utilizes residual steam from the boiler and then flows through nozzles to a flash tank filled with water. The nozzle converts pressure energy into kinetic energy to evaporate water briefly and release it to the condenser. Chilled water produced from the condenser cools the product through the transfer process. According to [1], the SJR system can be operated at a boiler temperature of 120 to 140°C and an evaporator temperature of 5 to 15°C. In general, 1% water evaporation in the tank can reduce the water temperature by 6°C [2]. The evaporator temperature is saturation temperature which depends on the evaporator pressure. Low pressure or vacuum in the evaporator is very dependent on the design of the nozzle (injector). According to [3], the ejector area ratio has a maximum corresponding to an optimum inlet pressure value. The optimum value decreases with a backpressure increase. Therefore, it is necessary to design the right injector for application in the steam jet refrigeration engine. As reported in [4], the optimum design inclination angle of the steam injector is 2o for the convergent type and 3o for the divergent type with a 137 mm throat length. However, due to the geometry injector, the efficiency or performance (COP) of the steam jet refrigeration engine is still very low.

As stated in [5], VCR-SJR system COP using refrigerant R 134a increased compared to the single SJR system. The problem is that the refrigerant R 134a includes hydrofluorocarbon (HFC) refrigerant, affecting global warming. Therefore, developing environmentally friendly hydrocarbon refrigerant (HC) technology is necessary. Using a hydrocarbon refrigerant such as isobutane (R 1234yf) is a good option for the VCR-SJR combination refrigeration machine [6]. However, this option is difficult to implement widely because refrigerant R 600a is only produced for certain brands of refrigeration machines. Therefore, alternative refrigerants that are environmentally friendly and widely available in the market are needed.

The technological innovation that will be applied in this research is the VCR-SJR combination refrigeration machine using a convergent-divergent type injector in the SJR unit and the VCR unit using MC 22 refrigerant. The performance of the SJR system highly depends on the efficiency of the nozzles, while the efficiency of the nozzle is influenced by the geometry and fluid pressure in the injector [7], [8]. This study aims to determine the characteristics of the working fluid flow in a Convergent-Divergent Injector in a Steam-Jet Compression Refrigeration Machine.

2. Literature Review

The operating principle of the SJR refrigeration machine is that steam from the boiler flows into an evaporator or flash tank through a nozzle. The nozzle suction side is connected to the evaporator, while the outlet side is connected to the condenser. Nozzles convert pressure energy into kinetic energy to decrease the vapor pressure. This pressure drop causes the vapor in the evaporator to be sucked in and then flowed to the condenser. The very fast evaporation of 1 kg of water results in a temperature decrease of 5.7°C [2]. If this condition continues, the water temperature will be lower as well. This can be done until it reaches the desired water temperature. The disadvantage of the SJR system is that water will freeze at 0°C, so it cannot circulate in the system. Due to these shortcomings, the application of the SJR system at low temperatures is very limited.

The VCR system refrigeration machine consists of four main components: compressor, condenser, expansion device, and evaporator. The heat is absorbed from the refrigerant to the cooling load in the evaporator.

The use of alternative refrigerants that are environmentally friendly, such as hydrocarbon refrigerants, is growing and widely used. This is understandable because hydrocarbon refrigerants do not contain Chlor, so it does not damage the ozone layer or cause global warming. The selection of alternative refrigerants for the 21st century must consider ODS elimination programs, system efficiency, global warming, safety, and costs [9]. Therefore, in producing alternative refrigerants, manufacturers consider the things proposed by Carter. In connection with this proposal, the ozone layer damage caused by HC refrigerant emissions decreased compared to CFC refrigerants [10]. This shows that the use of HC refrigerants is much better than CFC refrigerants.

Hydrocarbon refrigerants are the best choice for domestic refrigeration machines because they are environmentally friendly and energy-efficient [11]. More efficient use of energy positively influences the use of HC refrigerants. The increase in efficiency is caused by the density of the refrigerant HC being smaller than the density of CFC, so the compressor work is also lighter [12]. The SJR system performance is highly dependent on the efficiency of the nozzles, while the efficiency of the nozzle is influenced by the geometry and fluid pressure in the injector.

The influencing factors in injector design are the geometry between the water surface and the injector suction side. The ratio between inlet pressure and critical pressure depends on the injector geometry and the thermal properties of the working fluid [13]. Another important thing to consider is the mass flow rate of the primary flow [14]. The optimum geometry design of the steam injector is an inclination angle of 2° for convergent nozzles and 3° for divergent nozzles with a throat length of 137 mm [4]. On the output side, the parameter that affects the efficiency of the injector is the pressure drop [7]. Other factors to consider are critical pressure and shock waves at the injectors [15]. In addition, convection heat transfer below the boiling temperature is also important to consider [12].

3. Research Methodology

The secondary data visual fluid flow analysis in convergent-divergent injectors can be done by simulation using ANSYS 16.0, which has the FLUENT system analysis feature [16]. The first step of the simulation is to draw a convergent-divergent CAD injector using solid works. The second step implies import the convergent-divergent CAD injector into ANSYS using the geometry feature. At the third step, the convergent-divergent injector geometry is imported into the mesh. At the fourth step, the mesh is imported into setup, then set the solver based on pressure and steady-state problem in time type. At the fifth step, the energy equation is applied and the inlet and output pressures are set at the boundary conditions. Finally, the iterative solver and mixed initialization are selected, then the program is run.

Validation is done by testing an injector that has dimensions: suction chamber diameter 28 mm, nozzle inlet diameter 14 mm, suction chamber length 58 mm, secondary fluid inlet diameter (10, 15, and 20 mm), nozzle output diameter 5 mm, mixing length chamber 130 mm, throat length 95 mm, diffuser length 130 mm, and injector outlet diameter 40 mm. The injector is installed in a test circuit, as shown in Figure 1. The test is carried out by measuring several parameters, namely: injector steam inlet temperature, T7 (°C); the temperature of the steam and water mixture leaving the injector T8 (°C); injector steam pressure P3 (bar); the pressure of the steam and water mixture leaving the injector P4 (bar); flash tank inlet water temperature T7 (°C); T8 flash tank inlet water temperature (°C); flash tank inlet water pressure P5 (bar); and P6 flash tank outlet water pressure (bar). The temperature measurement uses a data acquisition system instrument, while the pressure and flow rate measurement uses an analog system instrument both on the VCR and the SJR units.

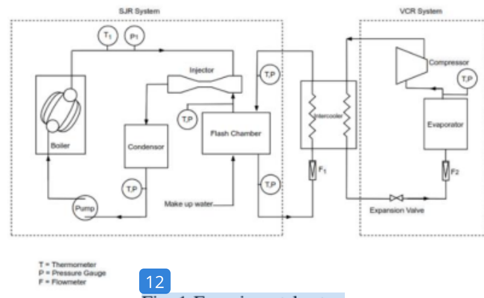


Fig. 1 Experimental setup

4. Results and Discussion

Figure 2 shows the static pressure variation inside the injector with a suction diameter of 10 mm. The high static pressure on the inlet side of the nozzle then drops after exiting the nozzle. Furthermore, the pressure drops drastically at a certain position and then tends to be constant until the injector exits. This is in line with the results of research conducted by [17].

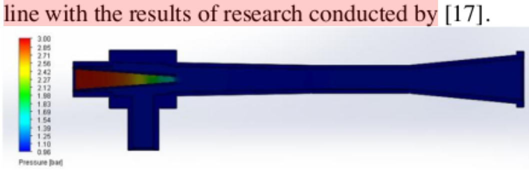
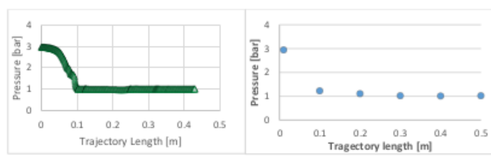


Fig. 2 Pressure contour with the suction diameter (d=10 mm)

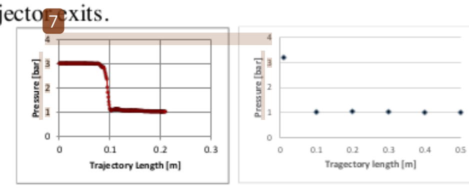


a. Simulation result b. Test result

Fig. 3 Pressure vs. trajectory length with the suction diameter (d=10 mm)

Fig. 4 Pressure contour with the suction diameter (d=15 mm)

As in Figure 2 before, Figure 4 shows the static pressure variation inside the injector with a suction diameter of 10 mm. The high static pressure on the inlet side of the nozzle then drops after exiting from the nozzle. Furthermore, the pressure drops drastically at a certain position and then tends to be constant until the injector exits.



a. Simulation result b. Test result

Fig. 5 Pressure vs. trajectory length with suction side diameter (d=15 mm)

Same as is the case with Figure 3, Figure 5 (a) also shows the simulation results of the pressure profile along the injector path, and the pressure profile conforms to the test results (b).

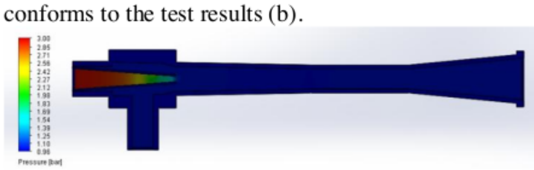
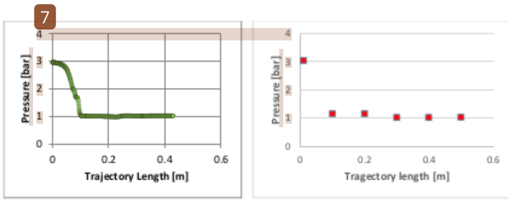


Fig. 6 Pressure contour with the suction diameter (d=20 mm)



a. Simulation result b. Test result

Fig. 7 Pressure vs. trajectory length with the suction diameter (d=20 mm)

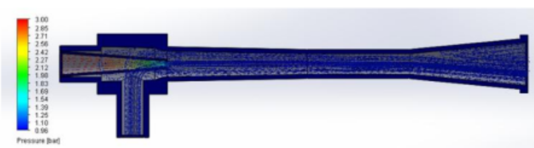


Fig. 8 Streamline with suction diameter (d=10 mm)

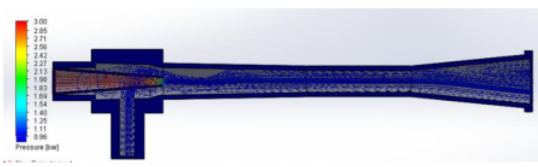


Fig. 9 Streamline with suction diameter (d=15 mm)

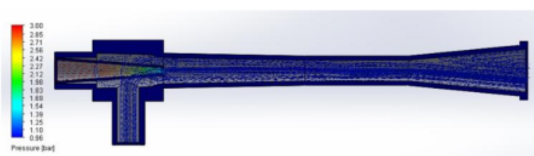
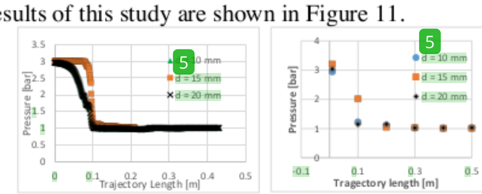


Fig. 10 Streamline with suction diameter (d=20 mm)

Figures 8, 9, and 10 show the uniformity of flow streamlines in the injector, especially around the axis along the path for the three variations of the injector suction diameter. However, Figure 9 shows a slight difference in flow, namely the occurrence of shock in the area of about 10 mm of the primary nozzle. This is influenced by the injector suction side diameter and complies with the previous research results [18], [19].

Simulation of working fluid flow in the injector has been carried out using ANSYS 16.0 and validated through testing on an injector testing installation which has dimensions: suction chamber diameter 28 mm, nozzle inlet diameter 14 mm, suction chamber length 58 mm, secondary fluid inlet diameter, d (10, 15, and 20 mm), the nozzle outlet diameter is 5 mm, the mixing chamber length is 130 mm, the throat length is 95 mm, the diffuser length is 130 mm, and the injector outlet side diameter is 40 mm. Figures 2 to 7 show the pressure contour, and the match between the simulation results and the test results is obtained. Therefore, the streamlined simulation results shown in Figures 8 to 10 are also quite accurate. The findings obtained from the results of this study are shown in Figure 11.



(a) Simulation result (b) Test result

Fig. 11 Pressure vs. trajectory length with the suction diameter (d)

Figure 11 shows the suction side diameters 10 mm and 20 mm have the same trend of pressure profile, but the 15 mm suction side diameter shows different things. This means that the injector geometry is very influential on the fluid flow, which will also affect the performance of the VCR-SJR refrigerating machine. These results are in line with the previous research results [20].

5. Conclusion

The simulation results of working fluid flow in the injector using ANSYS 16.0 and validation through testing on a testing installation of a convergent-divergent injector concluded that, in general, the injector geometry, especially suction side diameter, affects the flow profile of the working fluid in the injector. Validation is carried out by testing an injector that has dimensions: suction chamber diameter 28 mm, nozzle inlet diameter 14 mm, suction chamber length 58 mm, secondary fluid inlet diameter (10, 15, and 20 mm), nozzle outlet diameter 5 mm, mixing chamber length 130 mm, throat length 95 mm, diffuser length 130 mm, and injector outlet side diameter 40 mm. The profile of working fluid flow and pressure in the convergent-divergent injector with variations in the suction injector diameter had been determined. The pressure drops drastically at a certain position and then tends to be constant until the injector exits. However, the suction side diameter affects the flow profile of the working fluid in the injector. It is concluded that the characteristics of the working fluid flow in the injector on the VCR-SJR refrigeration machine are different at the various diameters of the suction side.

The carryout of this research will be applied as technological innovation of the VCR-SJR combination refrigeration machine using a convergent-divergent type injector in the SJR unit and the VCR unit using MC 22 refrigerant.

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