A Review of the Effect of Modification in Internal Parts on the Performance of Counter-Flow Vortex Tube

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Abstract - The vortex tube is a device which generates separated flows of cold and hot gases from a single compressed gas source. The main part of a basic vortex tube is a hollow cylinder, in which compressed air or other fluids are injected tangentially. The exits set at one or both ends of the tube allow hot and cold air to exhaust. As its performance is very low and in order to improve performance three innovative modification methods are explained in this paper. In the first method modifications are done in internal parts of vortex tube such as in nozzle intake, nozzle and added new part called a diffuser. Vortex tube developed with these modifications gives higher performance compared to conventional vortex tube. In second method new part called vortex generator which placed near the inlet of vortex tube and allows compressed gas to enter at different angles in vortex tube. Then performance parameters are evaluated. In third method hot tube of vortex tube is directly cooled by cooling jacket. Then performance is evaluated and compared to vortex tube without having cooling jacket. Out of three methods the vortex tube with modification in nozzle intake, nozzle and with added diffuser proves to be more efficient than other two methods explained here.

Keywords – Counter-flow vortex tube, cold mass fraction, diffuser, nozzle

1. INTRODUCTION

The vortex tube is a mechanical device that separates single compressed air stream into cold and hot streams. It consists of nozzle, vortex chamber, separating cold plate, hot valve, hot and cold end tube without any moving parts. In the vortex tube, when works, the compressed gaseous fluid expands in the nozzle, then enters vortex tube tangentially with high speed, by means of whirl, the inlet gas splits in low pressure hot and cold temperature streams, one of which, the peripheral gas, has a higher temperature than the initial gas, while the other, the central flow, has a lower temperature. Vortex tube has the following advantages compared to the other commercial refrigeration devices: simple, no moving parts, no electricity or chemicals, small and light weight, low cost, maintenance free, instant cold air, durable, temperature adjustable. Therefore, the vortex tube has application in heating gas, cooling gas, cleaning gas, drying gas, and separating gas mixtures, liquefying natural gas, when compactness, reliability and lower equipment cost are the main factors and the operating efficiency becomes less important.

There are two types of the vortex tube.1) Counter flow 2) Uni-flow. Both of these are currently in use in the industry. The more popular is the counter-flow vortex tube (Figure 1). The hot air that exits from the far side of the tube is controlled by the cone valve. The cold air exits through an orifice next to the inlet. On the other hand, the uni-flow vortex tube does not have its cold air orifice next to the inlet (Figure 2). Instead, the cold air comes out through a concentrically located annular exit in the cold valve. This type of vortex tube is used in applications where space and equipment cost are of high importance. The mechanism for the uni-flow tube is similar to the counter-flow tube. A radial temperature separation is still induced inside, but the efficiency of the uni-flow tube is generally less than that of the counter-flow tube. Although the vortex tube effect was known for decades and intensive experiments and correlative investigation had been carried out, the mechanism producing the temperature separation phenomenon as a gas or vapor passes through a vortex tube is not fully understood yet. Several different explanations for the temperature effects in the vortex tube have been offered.

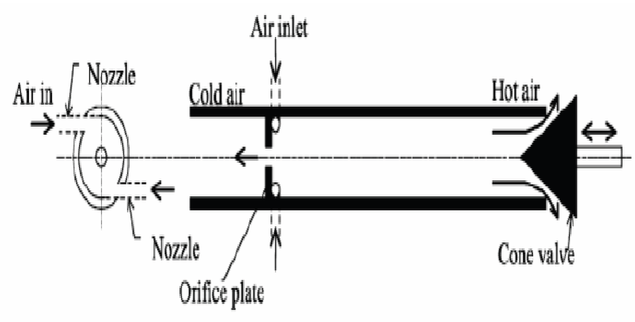


Fig 1 Counter flow vortex tube

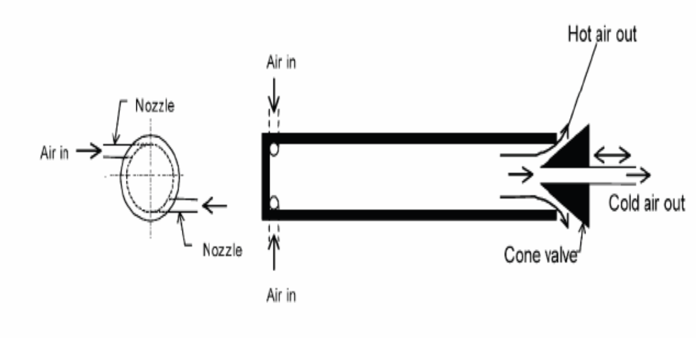


Fig 2: Uni-flow vortex tube

Hilsch firstly studied the mechanism of vortex tube and claimed that internal friction lead to the energy separation in vortex tube.Kassener and Knoernschild proposed that the conversion of an initially free vortex into a forced vortex result in a radial redistribution of energy. Stephan and Lin proposed vortices produced by tangential velocity as a main driving force for the energy separation in the vortex tube. Linderstrom-Lang assumed turbulent transfer of the thermal energy lead to the energy separation of vortex tube. A different theory was developed by Mischner and Bespalov they explained the energy separation mainly caused by entropy generation in vortex tube. Amitani et al. traced temperature separation to the compressibility of the working fluid. But Balmer concluded that the temperature separation phenomenon was not limited to compressible gases and vapors. While each of these explanations may capture certain aspects of vortex tube, none of these mechanisms altogether explained the vortex tube effect. As the efficiency of vortex tube is very low and In order to improve the efficiency of vortex tubes some innovative modifications in the internal parts of vortex tube are carried out which are explained in this paper.

2. Performance parameters

The most important parameter indicating the vortex tube performance is the cold mass fraction which can be expressed as:

$$\mu_c = M_c / M_i \qquad (1)$$

M_c – Mass of cold air at cold exit

M_i - Mass of compressed air at inlet

The cold gas temperature difference or the temperature drop of the cold air tube is defined as:

$$\Delta T_c = T_i - T_c \qquad (2)$$

T_i - Temperature of air at inlet

Tc – Temperature of cold air

The isentropic efficiency (η_{is}) of cooling process due to an expansion of gas in the vortex tube can be calculated via the following equation,

$$\Delta Tc = \eta_{is} \Delta T_{is} \qquad (3)$$

The property relation for isentropic process of ideal gas is applied for calculating the temperature difference in the isentropic process (ΔT_{is}):

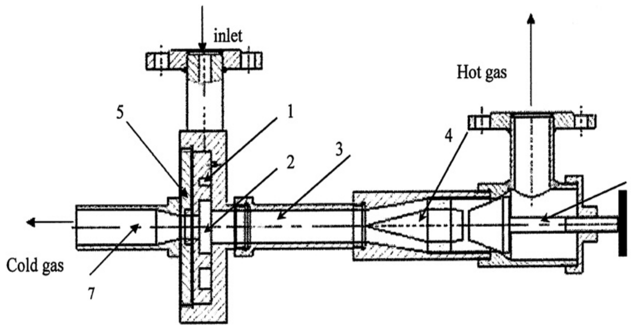
$$\Delta T_{is} = T_i \left(1 - P_a/P_i\right)^{(r-1/r)} \qquad (4)$$

Substituting Eq. (4) into Eq. (3) yields the general form of isentropic cooling efficiency of the vortex tube:

$$\eta_{is} = (T_i - T_c) / Ti \left(1 - P_a/P_i\right)^{r-1/r} \qquad (5)$$

3. Innovative modifications

Wu et al. [1] have carried out a lot of work to research how the parts of VT affect its performance by the measure of experiment. Based on these researches, they have proposed three innovative modifications in Nozzle, Nozzle Intake, and added diffuser at hot end of vortex tube to improve the performance of vortex tube. The schematic of vortex tube with modifications are shown as in Fig.3. He stated that in a conventional vortex tube, compressed gas directly enters a circular flow passage with equal section area from a straight pipe which can cause a sudden change of flow direction at the joint between the straight pipe and the circular flow passage. The sudden change would lead to the generation of eddies which cause the energy loss. In addition, the compressed gas flow flux decreased after a nozzle, but the area of flow passage keep unchanged, which cause a sudden reduction of flow velocity in the equation area circular flow passage. The sudden change of flow velocity and the eddy generated by the change would also cause the energy loss. In order to reduce the energy loss, a new design with equal gas flow velocity was proposed to keep the constant flow velocity and no sudden change for flow direction in the whole intake flow passage of nozzles. In the new design, as shown in Fig.4, firstly there is a smooth transition from an inlet straight pipe to circular pipe to avoid the sudden change in flow direction. Secondly, the area of circular flow passage decreases with the gas flux decreases, so the flow velocity in the whole circular flow passage can keep a constant flow velocity. Second modification is done in Nozzle of vortex tube. It is important to have a high peripheral velocity in the portion of the tube immediately after the nozzle, the curve of nozzle affect the performance of vortex tube. The conventional two types of nozzle are nozzle with normal rectangle and nozzle with Archimedes' spiral. A new nozzle as shown in Fig.5 was designed to minimize the flow loss. There are two features in the new designed nozzle. Firstly, the Mach number is the same in the section perpendicular to the axis of



nozzle. Secondly, Mach number along the axis of nozzle increases by the same gradient. The nozzle was called Nozzle with equal gradient of Mach number. Third modification is that a diffuser is installed before hot valve. The experimental data which is gained from the experiment with the

Fig 3. Schematic diagram of vortex tube. (1) Nozzle, (2) Vortex chamber, (3) Hot end tube, (4) Diffuser, (5) Separating cold plate, (6) Hot valve and (7) Cold end tube.

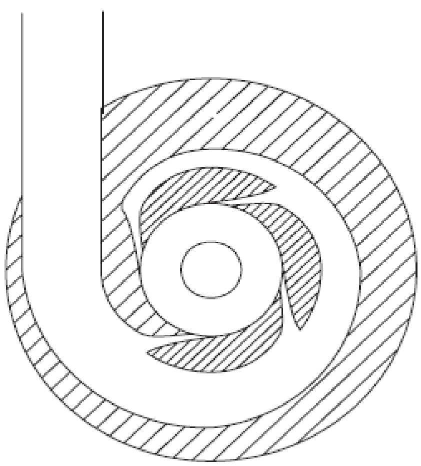


Fig.4 Design of new proposed nozzle

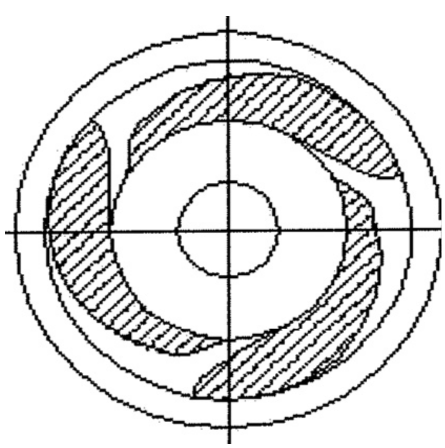


Fig. 5. Nozzle with equal gradient of Mach number.

conventional vortex tube tell that the airflow is still circumrotating strongly on the outlet of tube, so the friction loss of airflow energy is notable and this Energy loss is responsible for the result that the conventional vortex tube has poor performance. A diffuser installed before hot valve was designed to reduce the peripheral speed to zero within very short pipe and greatly reduce the ratio of length to

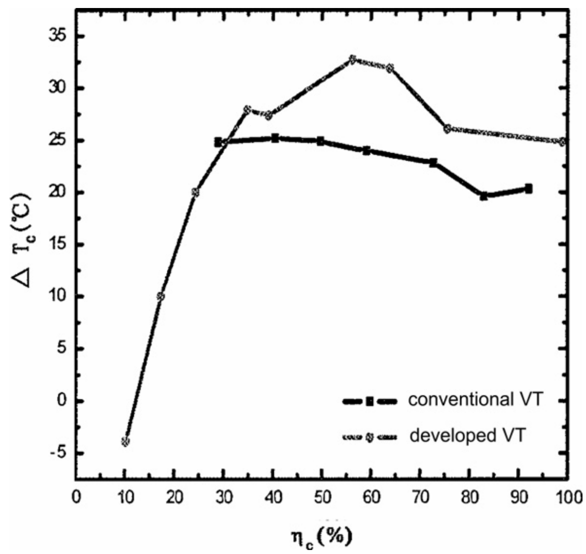


Fig.6 Comparison between conventional and optimized vortex tube in ΔT_c

At the same time, the diffuser can also reduce the viscosity loss and residual speed loss. The experimental results indicate that the cooling effect of the improved nozzle is about 2.2 ^{0}C lower than that of the conventional nozzle, the cooling effect of the vortex tube with diffuser is up to 5 ^{0}C lower than that without diffuser. The comparison of the performance between the developed vortex tube and conventional vortex tube is shown in Fig.6. The result indicates that the developed vortex tube has better cooling effect and temperature drop than that of original vortex tube.

Yunpeng et al. [2] have claimed that all the past works done are focused on the effect of length and diameter of the tube on tube efficiency and measurement of the parameters inside the tube. So he investigated the effect of the vortex generator configuration on tube efficiency. The experimental set up is as shown in Fig.7. In his study several structures named ‘‘angle generators” were placed in the vortex chamber to generate different vortex angles and investigated the influence of the vortex angle on the performance of the vortex tube. Compressed air with a regulated internal pressure of 7 bars was used as the working gas.

A pressure regulator was installed before the inlet nozzle to control the pressure of the air at the inlet. Angle generators were used in this experiment to develop vertical flows with different vortex angles. The angle generator was designed as an inclined surface which was attached to a hollow cylinder. The angle generators were fixed in the vortex chamber to be met initially by the injected air when it left the inlet nozzle. When the compressed air was injected into the inlet nozzle, it initially met the angle generator, which forced the airflow to align its direction with the angle of inclined surface of the

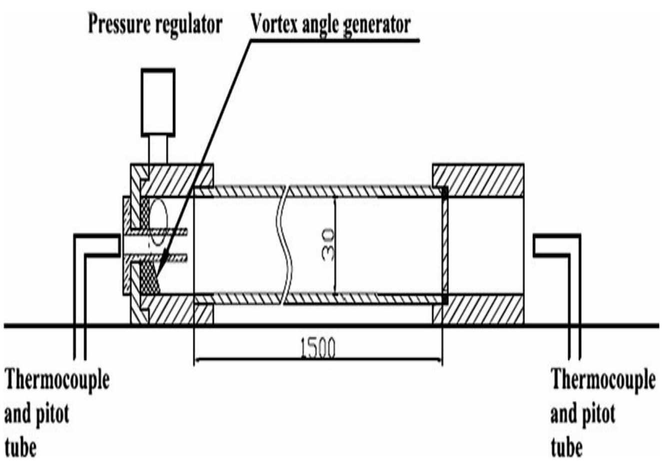


Fig. 7 Experimental apparatus for investigation of the vortex angle

Vortex generator. Despite the velocity and the vortex angle of flow change due to the viscous work along the tube, the air flew toward the hot end with a specific angle in the front part of the tube, in which most of the heat-transfer happens. Therefore, the influence of the vortex angle on the performance of the tube can be investigated. Different angle generators were used in this test to obtain various vortex angles of the air flow. A small tube was used to separate the injected air and the cold air. The tube was positioned in the vortex chamber through the cold nozzle and the hollow centre of the angle generator. Thus, it could be assumed that direct mixing of the air feeding into the tube and the cold portion of the air leaving the cold orifice did not occur during the experiment. During the experiments, temperature was measured by a thermocouple and the exhausting air pressure was measured by a pitot tube. The thermocouple and pitot tube were fixed at a distance of 50 mm from the exhaust nozzle and along the centerline of the tube. In the experiments, both the angle generators and the input pressure were changed in order in which way a smaller temperature difference between any two sequential tests occurred. Thus, less heat transfer is helpful to reduce the reaction time. The results indicated that the vortex angle played an important role in both the separation of cold and hot flows and the vortex tube performance. A smaller vortex angle demonstrated a larger temperature difference and better performance for the cooling efficiency of the vortex tube. Fig. 8 shows the temperature of the cold air at different input pressures. It can be seen that using the smaller angle generator increases the temperature difference between the ambient air and cold portion of the flow. Moreover, the temperature drop of the cold air rises with the increase of the input pressure for a certain vortex angle. The temperature drop of the cold air rises with the reduction of the vortex angle or

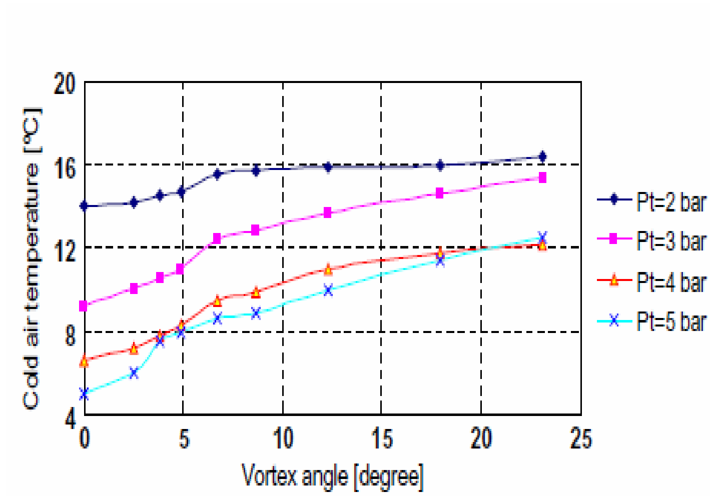


Fig.8. Temperature of the cold air for different vortex angles

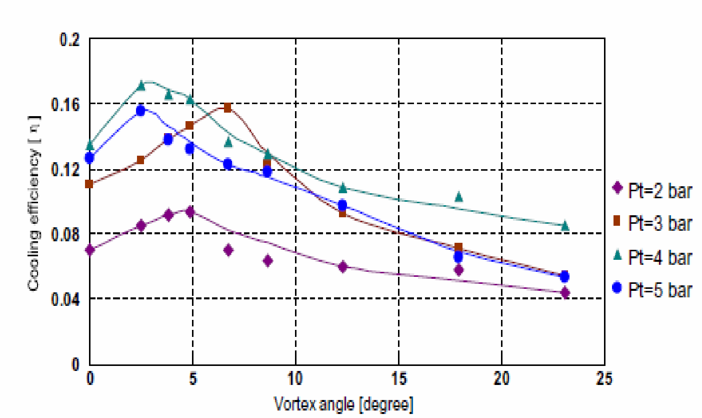


Fig.9.Cooling efficiency of the vortex tube versus vortex angle.

increase of the input pressure. Cooling efficiency of the vortex tube increases when the vortex angle decreases or input pressure increases as shown in Fig.9.

S. Eiamsa-ard et al. [4] Studied the effect of cooling of hot tube on the energy/temperature separation and cooling efficiency of the vortex tube. The experimental set up is as shown in Fig.10.In this system a cooling water jacket is assembled around the hot tube wall of the counter-flow vortex tube to function as a heat receiver of the hot gas in the peripheral region of the vortex tube. It is expected that cooling effect will promote heat transfer from inner region to outer region of the vortex tube and offer higher cooling efficiency of the vortex tube. The study focuses on the influence of the cooling system on the temperature separation (the temperature reduction of cold air) and cooling Efficiency characteristics. The inner tube or hot tube of counter flow vortex tube is covered with cooling

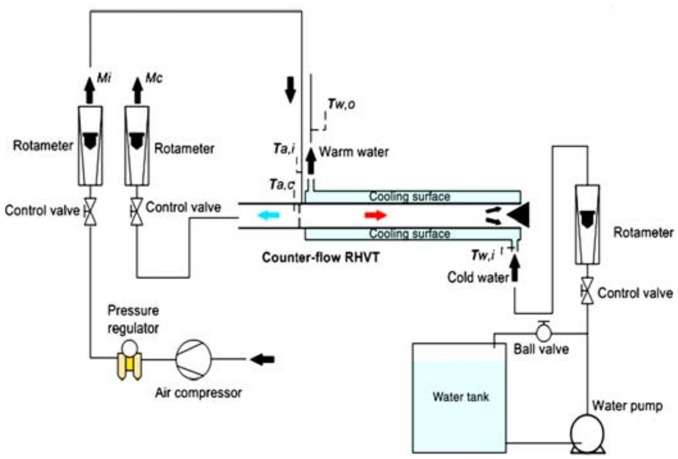


Fig.10 Schematic of the experimental Apparatus.

jacket through which cold water is circulated constantly.

In the experiments, the inlet and cold air temperatures were measured by thermocouples while the mass flow rates at the inlet and outlet of tube was measured using orifice meters. A calibrated water rotameter was applied to measure the flow rate of the cold water. The experiments were carried out at various cold mass fractions, varied between 0 and 1 and for single nozzle while inlet pressure and temperature were kept const at 2.5 bars and 27 °C, respectively. The results reveal that the highest values of the temperature reductions found to be 17.4 ° at the cold mass fraction of around 0.31.as shown in figure 11. The RHVT with the cooling of a hot tube provides greater temperature reduction of the cold air and cooling efficiency than one without the cooling of a hot tube as shown in figure 12. This can be due to the fact that the cooling water jacket plays a role as thermal receiver for the hot gas in the outer (peripheral) region of the vortex tube and helps to enhance the compression of the hot gas. This effect would subsequently enhance the expansion of cold gas in the inner region, resulting in superior temperature reduction of the cold gas and thus, cooling efficiency. In other words, the cooling water promotes the energy transfer from the inner region to the outer region of the vortex tube. For all test runs, both temperature reduction and cooling efficiency of the cold air significantly increase with the increase of the cold mass fraction (μc) ranging from 0.1 to 0.4. However, the opposite trend is found beyond the cold mass fraction of 0.4. It can be concluded that the optimum conditions are at the cold mass fraction ranging from 0.3 to 0.4.

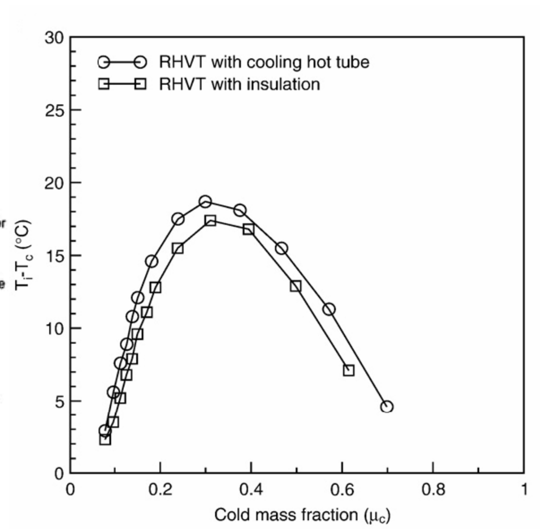


Fig. 11 Effect of the cooling of a hot tube on cold air temperature reduction

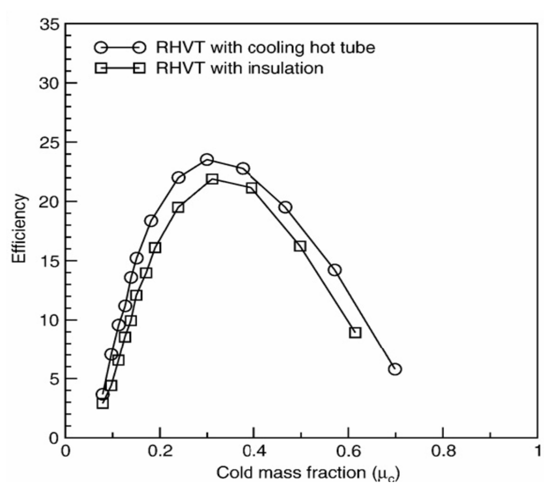


Fig.12 Effect of the cooling of a hot tube on cooling efficiency

Name of Method	Input Pressure (bar)	Cold temperature drop (Ti-Tc) ^{0}C	Cooling efficiency (%)	Cold mass ratio
Innovative modification in i) Nozzle Intake, ii) Nozzle. iii)Adding a diffuser	0-16 bar	33^0 C	57%	kept constant
Enhancement by varying vortex angle	2-5 bar	(Ti-Tc) Increases with smaller vortex angle and higher input pressure	Cooling efficiency increases with smaller vortex angle value obtained is 15.6 at 3 bar	Increases with decrease in vortex angle and increase in input pressure
Enhancement by cooling hot tube	2.5 bar	(Ti-Tc) Increases and value obtained is 17.4 at cold mass ratio 0.3	Increases and value obtained is 23.5 at cold mass ratio 0.3	0.3

TABLE 1 Comparison between methods in terms of performance parameters

4. CONCLUSION

In this paper three methods of enhancement of performance of counter flow vortex tube are explained. Moreover the performance parameters are evaluated for each method. After comparing performance parameter obtained by each method. It is concluded that counter flow vortex tube with modification in nozzle intake, nozzle and with added diffuser provide maximum performance compared to other two method explained in this paper.

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