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The cooling efficiency of different dental high-speed handpiece coolant port designs

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ABSTRACT

The study investigated the cooling efficiency of different numbers of water coolant ports on high-speed handpieces (HSH) under cooling conditions used in clinical practice.

Twenty-four groove cuts with water on and nine cuts without water were made on extracted human premolars using three HSHs with different port configurations. Thermocouples were placed in the pulp chambers and temperature changes were recorded with 1-, 3- and 4-coolant port handpieces. Cooling rate was calculated for each coolant port design system. Temperature changes were statistically analysed with Kruskal-Willis Test.

All three sample groups resulted in a net temperature decrease during the cutting period with water turned on. There was a pattern of increased cooling rate with increasing number of coolant ports (1-port: -4.27 (±0.94) °C, 3-port: -4.66 (±2.90) °C, 4-port: -5.03 (±1.08) °C). The difference was not statistically significant ($p = 0.681$). Calculations of cooling rate showed a higher cooling rate with an increase in the number of ports (1-port: $46.13 \times 10^{-4}\ K^{-1}$, 3-port: $51.36 \times 10^{-4}\ K^{-1}$, 4-port: $56.32 \times 10^{-4}\ K^{-1}$). In the dry tooth preparation samples, all resulted in a net increase in temperature (1-port: 4.43 (±3.30) °C, 3-port: 5.13 (±3.27) °C, 4-port: 2.87 (±2.97) °C).

All the three water coolant port configurations showed effective cooling of the tooth during cutting and decreased pulpal temperature with no statistical difference. There are HSH designs with varying numbers of coolant ports available in the market for clinicians. The results of the current study could potentially aid clinicians in making a decision while choosing between different dental handpieces.

1. Introduction

In dentistry, the high-speed handpiece (HSH) is a commonly-used equipment in clinical settings for fast and efficient removal of tooth structure in the restoration process [1]. A good HSH should have sufficient cooling features to reduce the heat produced by the friction between the bur and tooth surface [2]. Excessive heat transfer results in inflammation and necrosis of the pulp [3]. This can be measured by a temperature increase in the pulp chamber. The reference temperature increase of 5.5 °C found by Zach and Cohen (1965) is often used as the threshold in *in vitro* temperature studies, and any temperature change above this is regarded to have detrimental effects on pulp [4]. Over time, summation of irritating stimuli may also result in a chronic inflammation with no clinical symptoms, before progressing to more severe irreversible pulpal damage [5, 6]. The response of the pulp following irritation depends on the health of the pulp, the extent of tissue damage, and the action of the inflammatory mediators [7]. The reference temperature of 5.5 °C used in *in vitro* experiments is an acceptable threshold for healthy pulp tissue. However, hyperemic pulp is more sensitive to changes in temperature [8]. Therefore, it is important to minimise iatrogenic thermal irritation to the pulp.

Most modern HSHs incorporate air or air-water coolant ports, which are designed to spray water at the bur-tooth interface, to improve the cutting and cooling efficiency, and to minimise the pulp injury [1, 2, 9]. However, a photographic study found that the coolant has effect on the entire tooth, as the droplets are deflected from the air whirl created by the spinning bur, with more water deflection at high speeds [10].

Fluid in the dentinal tubules transfers heat generated from the cutting surface of the tooth to the pulp [11]. The thickness of dentine remaining between the cutting area and the pulp, and area of dentine tubules cut are factors to consider in the temperature change experiments [3, 12]. It is well-established that water coolant is important for preventing an iatrogenic damage due to frictional heat and while cutting, a HSH should not be used without a water coolant [13, 14].

Previous studies on the number of coolant ports have suggested a link to increased cutting efficiency with increased number of ports [15]. We

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Table 1
Specifications of handpieces used.

Number of Ports	Model name	Power (W)	Speed (kRPM)	Head Size
1	NSK Pana-Max2 M4	20	350–450	⌀10.8
3	NSK Ti-MAX X450L	21	380–451	⌀11.2
4	NSK S MAX M500L	16	380–450	⌀10.6

have found that this is not the case. Reduced cutting efficiency and debris clogging result in concentration of frictional heat which in turn leads to an increase in pulpal temperature [5]. One study found an improvement in cutting efficiency with 3- and 4- ports while making groove cuts [15], while other studies found no significance [16]. This may be due to the different arrangements of the coolant port and bur, which consequently impacted coolant accessibility to the surface. From a theoretical standpoint, more water ports may provide more efficient cooling as water is distributed more evenly to all cutting interfaces and cutting efficiency is improved. A trend by handpiece manufacturers promoting the sale of handpieces with extra coolant ports predicated on the assumption that additional cooling ports provide more efficient cooling.

No study has been conducted on the effect of number of coolant ports on cooling efficiency. Therefore, the purpose of this study was to examine the cooling efficiency of different number of water coolant ports on HSHs under cooling conditions used in the clinical practice. The null hypothesis for the current study is that the different number of water coolant ports would have no influence on the cooling efficiency of high-speed handpieces.

2. Materials & methods

Non-carious and non-restored extracted premolar teeth were collected from the University of Otago Faculty of Dentistry with ethical approval (University of Otago Human Ethics Committee - H18/096). All the teeth were stored in formalin immediately after the extraction and were stored in artificial saliva (Biotene; GSK, United Kingdom) for a week prior to testing.

The roots of the teeth were sectioned off below the cemento-enamel junction to allow access (MOD 13 Diamond wheel; Struers, Germany) and the pulpal chambers were cleaned with endodontic K-files (Ready-Steel; Maillefer Instruments, Switzerland) and sodium hypochlorite. The coronal portion of the teeth were fixed onto CAD-designed (AUTOCAD 2018; Autodesk, USA) and 3D-printed (Form 2; Formlabs, USA) water-bath boxes (28 mm × 28 mm × 32mm), with the box assembly being pushed with a constant load against the stationary HSH for cutting. The temperature in pulp chamber was maintained at 37 ± 0.6 °C. Temperature measurements were recorded with thermocouples (k-type thermocouple; Omega, USA) inserted into the pulp chamber of each tooth. Placement of the thermocouples in the middle of the pulp chamber was confirmed with radiographs taken from different perspectives (Sirona Xios XG; Dentsply, USA). Pulpal cavities were subsequently filled with a high-density polysynthetic silver thermal compound (Arctic Silver 5; Arctic Silver Incorporated, USA) to improve conductivity within the tooth.

The water reservoir for the coolant water was maintained at 22.4 °C. Three different high-speed handpieces (NSK-Nakanishi International, Japan) with 1-port, 3-port and 4-port designs respectively were used. Each handpiece presented with different specifications designed and are marketed for different purposes as listed in Table 1 and each the handpieces with water sprays in action are shown in Fig. 1.

The HSH speeds and water flow rates were maintained by an input drive air pressure of 250 psi and input spray air pressure 100 psi. The free-running speeds of each handpiece were measured with a tachometer (HPW-2 Handpiece counter 2; Micron, Japan) and coolant flow rates were measured gravimetrically.

Tooth cutting was performed with the testing apparatus which is depicted in Fig. 2. The water-bath box containing the tooth crown was pushed towards the fixed handpiece, using a stress and tension gauge (Correx tension gauge; Haag-Streit, Switzerland) at a constant force of 1.0 ± 0.2 N to simulate the force applied by the dental practitioner during cutting. Before cutting, friction against the box was tested with the same gauge and found to be negligible.

The cutting technique adopted was 30 s of cutting, 30 s of rest, and another 15 s of cutting. A new cylindrical, medium-grit, tapered, diamond bur (847R/5/016; Meisinger, Germany) was used for every new cut.

Since it was a study with no existing data to calculate a suitable sample size, a pilot study was conducted ($n = 3$) to perform a sample calculation using G. Power (Universität Düsseldorf, Germany) which revealed that having minimum 7 specimens will show the specimens cooling difference with the power of 0.8. Hence, twenty-four groove cuts were made with 3 HSHs with water coolant and the cuts were repeated with the same 3 HSHs in the dry setting such that each coolant port group performed eight cuts. Groove cuts were made 2 mm away from the edge of the tooth. The remaining dentine thickness was measured post-cutting using a method of embedding and slicing. The cutting groups were randomly assigned to minimise any bias due to tooth morphology.

Real-time temperature and duration were recorded at 2 s intervals throughout the entire cavity preparation process using a digital data logger (GFX Data Logger Series and EL-USB-TC; Lascar Electronics Inc, USA), and the data was retrieved using EasyLog Software (EasyLog USB; Lascar Electronics Inc, USA).

Statistical analysis was performed (SPSS Ver 24, IBM, USA) for the change in temperature using a non-parametric Kruskal-Willis Test. The cooling rate (cooling coefficient, k) was calculated for each coolant port design system (temperature data was converted to Kelvin) using the Newtons Law of Cooling formula [17].

$$T(t) = T_s + (T_0 - T_s)\, e^{(-kt)}$$

$T(t)$=*Temperature (Kelvin) at time t,* T_s=*surrounding temperature (Kelvin),* T_0=*Temperature (Kelvin) at time 0,* k=*cooling coefficient* (K^{-1}), t=*time (s)*

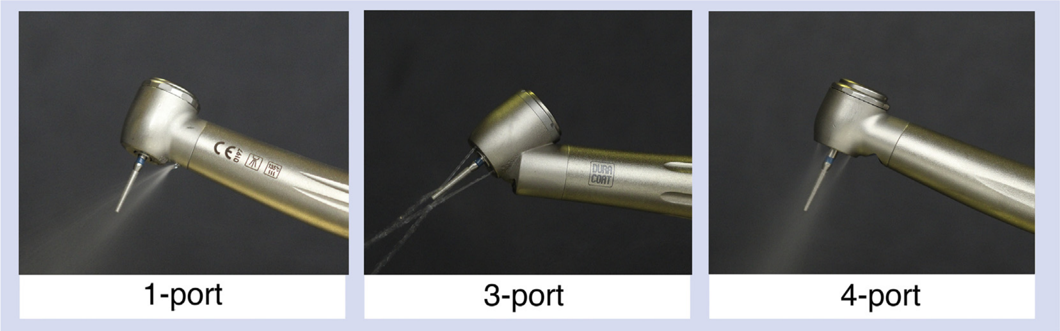

Fig. 1. Water coolant coming out of the 3 different handpieces used in the current study.

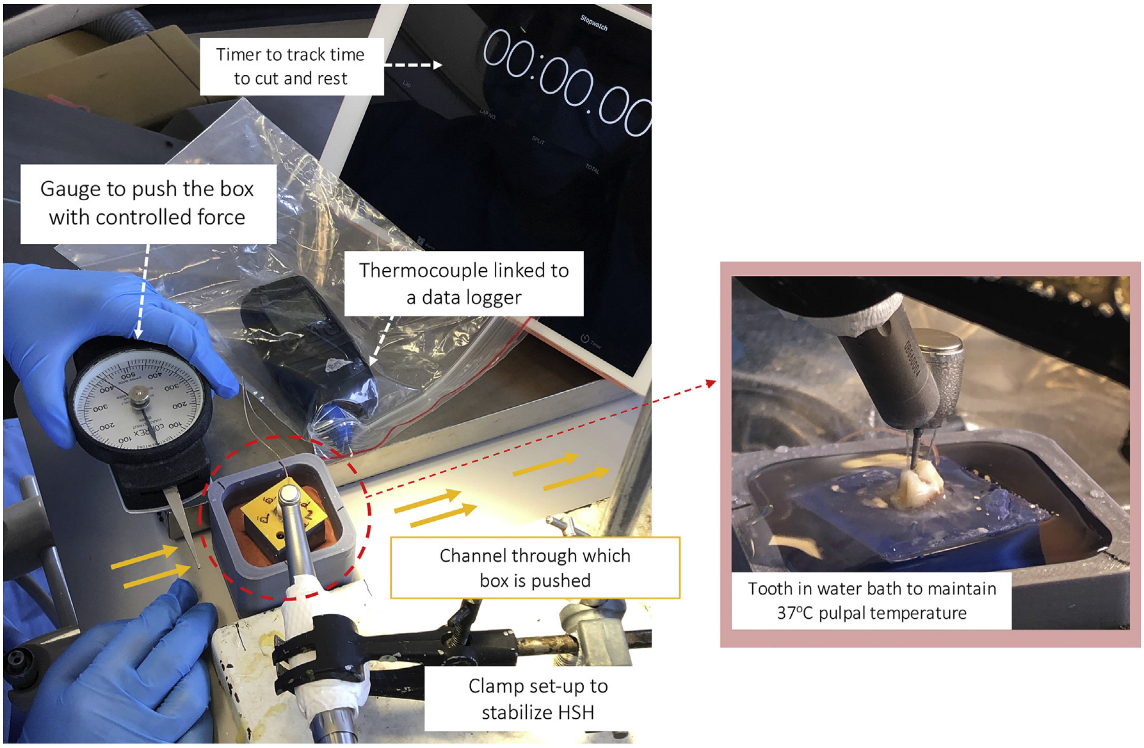

Fig. 2. Testing apparatus and experimental set-up.

3. Results

The samples with water coolant showed a decrease in net temperature while samples without water coolant showed an increase in net temperature (Fig. 3). The mean temperature change for 1-port air-water group was -4.27 °C (±0.94), for 3-port air-water group was -4.66 °C (±2.90) and for 4-port air-water group was -5.03 °C (±1.08) group (Table 2). All three groups with water coolant followed a similar curve in temperature decrease. Although observed temperature changes showed a pattern of improved cooling with increasing number of ports, statistical

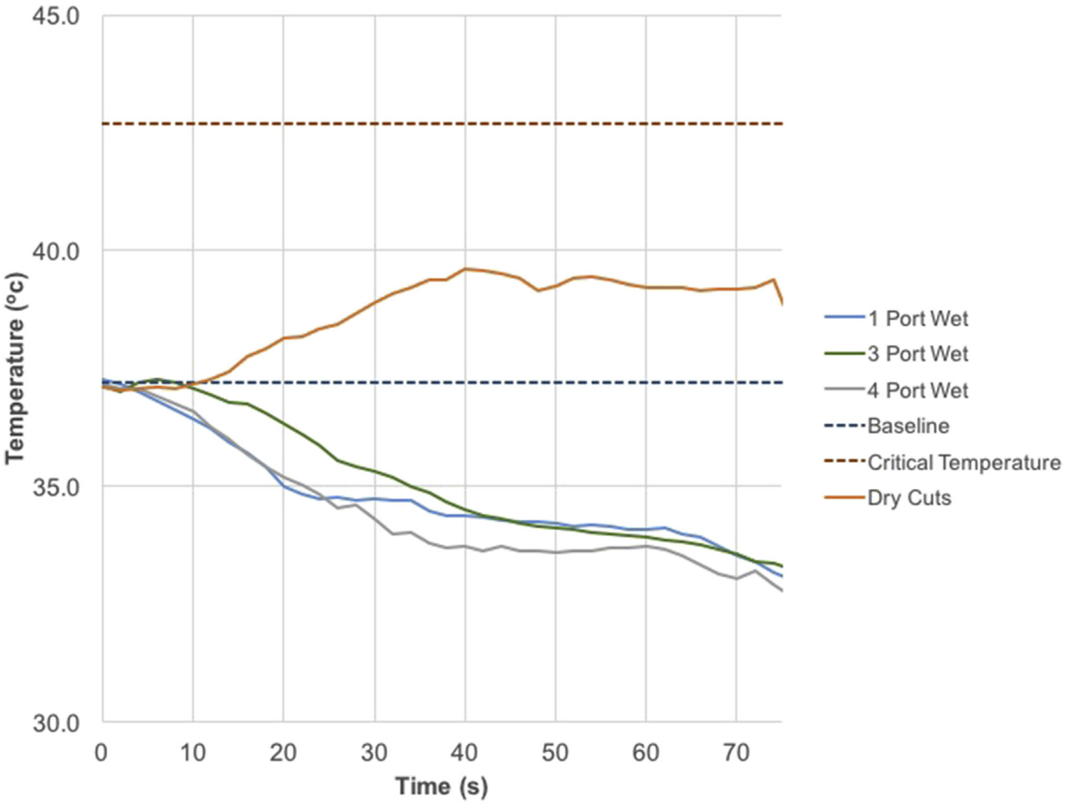

Fig. 3. Mean pulpal temperature change over time for all test group.

Table 2

Mean temperature, standard deviation, p value and calculated cooling coefficient.

	Mean (±S.D) temperature change (°C)	P value	Cooling coefficient (K^{-1})
1-port air-water	-4.27 (±0.94)	0.68	46.13×10^{-4}
3-port air-water	-4.66 (±2.90)		51.36×10^{-4}
4-port air-water	-5.03 (±1.08)		56.32×10^{-4}
1-port dry	4.43 (±3.30)	0.49	Not applicable
3-port dry	5.13 (±3.27)		
4-port dry	2.87 (±2.97)		

analysis revealed no significant difference ($p = 0.681$).

Fig. 4 presents the data recording of each sample over time. All samples with air-water spray coolants showed net decrease in temperature. Six out of the eight samples in the 3-port group had a slight increase in temperature (ranging 0.1–0.8 °C) before decreasing. Of the 4-port group, only one sample had a slight increase in temperature (1.2 °C) before decreasing. All the samples in the 1-port group showed immediate decrease in temperature as cutting began. All 3 curves follow a similar pattern with constant decrease in temperature. However, there was more variability within 3-port and 4-port groups.

For dry specimens, the mean temperature change was 4.43 °C (±3.30), 5.13 °C (±3.27), 2.87 °C (±2.97) for 1-port, 3-port, 4-port respectively.

Free-running speed and water coolant flow rate were recorded in Figs. 5 and 6. The 3-port design displayed the fastest free-running speed, followed by 1-port, then 4-port (Fig. 5). Water coolant flow rate showed an inverse correlation with number of ports; a decrease in flow rate was seen with an increase in number of ports (Fig. 6).

4. Discussion

Data from this study showed a net decrease in pulp chamber temperature when air-water coolant was used, and net temperature increase when no water was used. This is consistent with some previous studies [2, 18, 19]. Previous studies have shown that load and water flow rate are significant factors that affect the change in temperature.

Cutting without water coolant is established to result in increased temperature due to friction and heat production that is likely to cause iatrogenic damage if it rises above the critical 5.5 °C. The current study observed that the temperature increase while preparing the tooth with the HSHs without a water coolant (1-port: 4.43 (±3.30) °C, 3-port: 5.13 (±3.27) °C, 4-port: 2.87 (±2.97) °C) remained below the critical value of 5.5 °C. This is likely due to differences in methodology compared to previous studies, such as the pulpal simulation and temperature and flow rate of water coolant used, and the cutting technique.

In this study, pulp conditions were simulated by keeping a water bath at the temperature of 37 °C. Heat transfer experiments conducted without pulpal simulation at room temperature resulted in temperature increase of a greater magnitude than experiments with pulpal simulation [20]. In a previous *in vitro* study, decreased temperature was observed when the cooling water was 33.7 °C or less, with pulpal and cutting environment maintained at 34 °C [12]. Our current study used 37 °C as the baseline pulpal temperature, assuming that pulpal temperature is the same as physiological temperature. A more recent study has suggested that the pulpal temperature may be lower than that [21]. It is unclear if using a different baseline temperature would affect the temperature changes.

The current study adopted a less aggressive intermittent cutting technique, which could have influenced the temperature changes observed. Previous studies have found that intermittent cutting results in lesser temperature increase and studies recommend this to clinicians [12, 19]. Furthermore, the temperature of the coolant water used in this experiment was 22.4 °C, direct from the water source. This is considerably lower than what was used in experiments that found temperature increases above 5.5 °C [2, 12, 22]. The flow rates used in this current study were similar to the typical flow rates used in dental practice and the recommended coolant flow rates [2, 23, 24].

The water bath set up to simulate pulpal conditions during the experiment also lost heat 0.5 °C over 80 s. Any resultant decrease in temperature could be to be over-estimated, and resultant increase in temperature was likely to be under-estimated. In clinical condition, the flow of blood through the pulp normally regulates pulpal temperature and is slowed with the use of vasoconstrictor-containing anaesthetics. Thermal stimulants may result in greater temperature increase in clinical settings where the pulpal blood flow does not dissipate effectively [25, 26]. Further investigation of the effect of different water coolant port designs could employ another novel method using tooth slices to analyse the response of the pulpal irrigation [27]. In future studies, a better pulpal simulation experimental set up would be helpful to find the exact temperature change during the tooth preparation.

While the current study aims to control other possibly confounding factors, the remaining dentine thickness could not be fully controlled due to difference in size and shapes of the teeth. The less the remaining dentine thickness is, the more the pulpal temperature will be affected by external stimuli [11]. The current study controlled this by using teeth that were similar in size and performing same sized cuts. The coolant port groups were also randomly assigned to each tooth/side of the tooth to prevent bias. The mean remaining dentine thickness of the tooth samples was 0.94 ± 0.46 mm. In the current study, these factors were sufficiently controlled several internal and external factors, that may influence this cooling effect, in order to determine the influence of the number of ports on cooling.

All three coolant port designs showed an overall decrease in temperature, thus rejecting the null hypothesis of the current study. However, it is expected that other factors such as the dimensions of the coolant port aperture or coolant water velocity, could also contribute to the cooling process. Further research on these parameters would shed light on the degree of their contribution.

5. Conclusion

All the three water coolant port configurations showed effective cooling of the tooth during tooth preparation and decreased pulpal temperature (range of mean temperatures: -4.27 to -5.03 °C). The trend observed here was the handpieces with a higher number of cooling ports showed a greater degree of cooling despite there being no significant temperature change when compared to the other coolant port configurations.

Declarations

Author contribution statement

Helene Chua, Joanne Jung Eun Choi & John Neil Waddell: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Rishi Sanjay Ramani & Ritu Ganjigatti: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

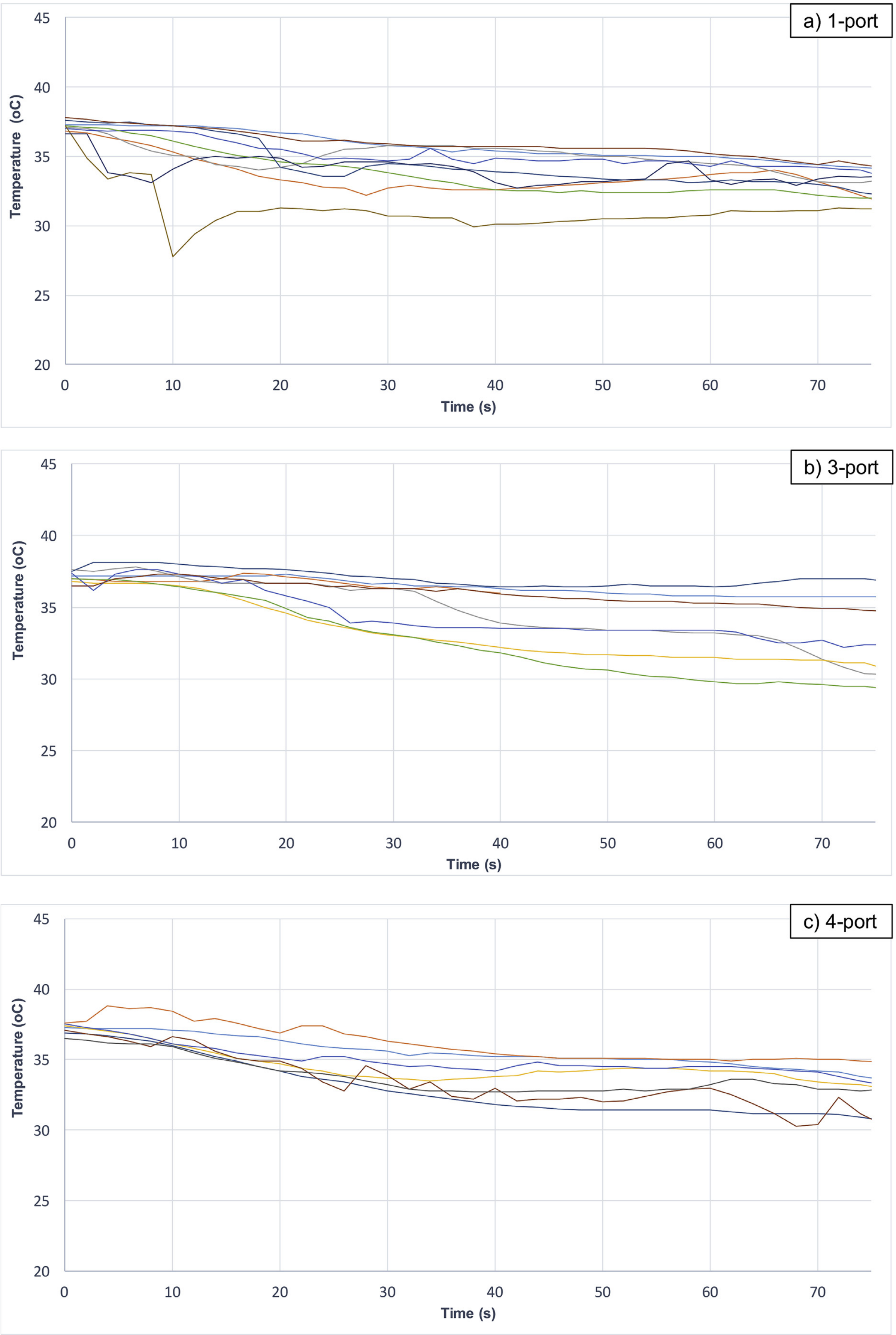

Fig. 4. Real-time temperature change in pulp chamber over time for each group; a) 1-port HSH b) 3-port HSH c) 4-port HSH.

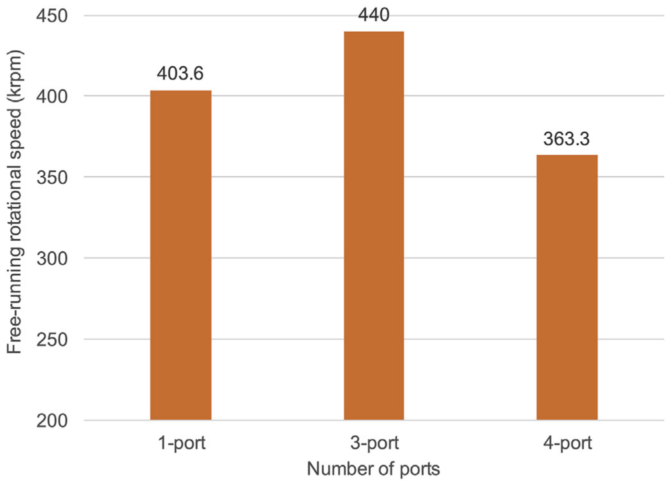

Fig. 5. Measured free-running speed for each port designs at the same air pressure.

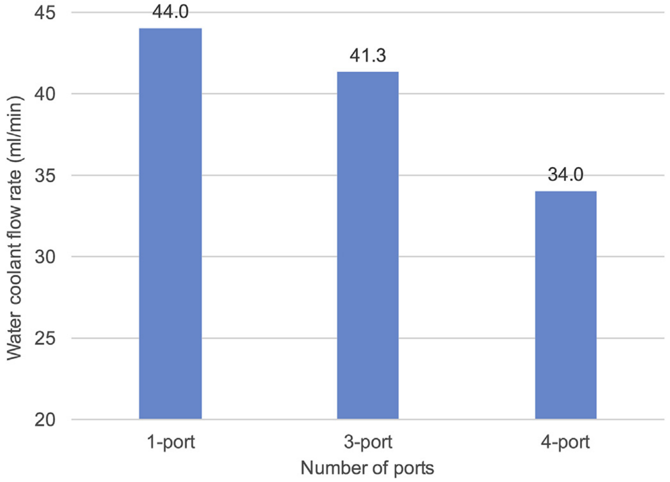

Fig. 6. Gravimetrically measured water coolant flow rate for each port designs at the same air pressure.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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