

Methodology for Comparison of Hydraulic and Thermal Performance of Alternative Heat Transfer Fluids in Complex Systems

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A general method for the comparison of hydraulic and thermal performance of different liquid coolants in complex systems is offered. As a case study, the performance of polyalphaolefin (PAO) and a silicate ester-based fluid (Coolanol 25R) used as liquid coolants in avionic systems is presented. Thermophysical property expressions for the variation of density, specific heat, thermal conductivity, and kinematic viscosity with temperature for PAO and Coolanol 25R were developed. The range of temperature for this study was from -54 to 135°C . Based on the results, the hydraulic performance of Coolanol 25R is much better than that of PAO at low temperatures (below 0°C) and in the laminar flow regime. In the turbulent region, PAO outperforms Coolanol 25R hydraulically over the entire temperature range. The thermal performance of PAO at temperatures below 61°C and in the laminar flow region is slightly better than that of Coolanol 25R. In the low-temperature turbulent region, Coolanol 25R outperforms PAO thermally. At other temperatures, the performance of the two liquid coolants is reasonably close and fairly independent of the flow regime.

Silicate ester-based fluids (e.g., Coolanol 25R) are widely used as dielectric heat transfer fluids in the Air Force and the Navy airborne radar and missile systems. These fluids have caused significant and sometimes catastrophic problems due to their hygroscopic nature and subsequent formation of flammable alcohols and silica gel. The alcohol by-product lowers the fluid flashpoint, in-

creasing the risk of aircraft fires. The gelatinous precipitate, called the "black plague," deposits on transmitter surfaces and components, causing avionics equipment to malfunction.

In order to solve the problems associated with silicate ester-based fluids, the Naval Air Development Center and the Air Force Materials Directorate investigated the possibility of direct replacement of silicate ester-based fluids with hydrogenated polyalphaolefin-based fluids. Their studies concluded that polyalphaolefin (PAO) fluids are chemically more stable (they do not hy-

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drolyze to form either silica gel or alcohol by-products), less costly, offer equal or improved dielectric characteristics, and meet or exceed military requirements for a dielectric coolant [1–4].

Because of the inherent desirable properties of PAO, their ready availability, and their relatively low cost (about one-fifth of the cost of current silicate ester-based fluids), the Air Force and the Navy have both replaced the current heat transfer fluid in the avionics system with PAO for some selected aircrafts. Although replacement of silicate ester-based fluids with PAO fluid reduces the risk of aircraft fire and eliminates the coolant fluid contamination problem that results in “black plague,” the overall performance of the avionics liquid cooling system with PAO in comparison to silicate ester fluids over a wide temperature range has not been fully studied. Limited unpublished studies have been conducted on the performance of specific aircraft radar transmitters with PAO [2, 3].

The objective of this study was to develop a simple methodology for comparison of hydraulic and thermal performance of alternative heat transfer fluids in complex systems, and specifically to compare the hydraulic and thermal performance of PAO and a silicate ester-based fluid (Coolanol 25R) in a temperature range (–54 to 135°C) applicable to avionics equipment. Both laminar and turbulent flow regimes were considered. In order for the analysis to be general, variation of dimensionless system parameters with temperature are presented. In addition, as part of this study, equations were developed for the variation of thermophysical properties of Coolanol 25R and PAO with temperature.

THERMOPHYSICAL PROPERTIES EQUATIONS

Knowledge of thermophysical properties of the Coolanol 25R and PAO fluids as a function of

fluid temperature was required for hydraulic and thermal performance analysis. Thermophysical property data for Coolanol 25R and PAO (Brayco Micronic 889) were obtained from technical data sheets provided by Chevron [5] and Castrol [6], respectively. The density (ρ), specific heat (c_p), and thermal conductivity (k) data were easily curve-fitted in the form of a polynomial in temperature using a least-squares curve-fitting program. The degree of the fitted polynomial, in some cases, varied between the two fluids for the same thermophysical property. In order to avoid listing several different equations, the general form of the curve-fitted equation with the highest obtained degree of polynomial is presented in the form

$$[\text{PROPERTY}] = A + BT + CT^2 + DT^3 + ET^4 + FT^5 \quad (1)$$

In Eq. (1), the term PROPERTY can be either density in kg/m^3 , specific heat in kJ/kg K , or thermal conductivity in W/m K , and the temperature (T) is in K. The curve-fitted constants A to F to be used in Eq. (1) for Coolanol 25R (C25R) and PAO are tabulated in Table 1. The curve-fitted equations for ρ , c_p , and k predict the Coolanol 25R and PAO data with a maximum deviation of less than $\pm 0.5\%$.

For variation of kinematic viscosity with temperature, the viscosity–temperature relationship suggested for petroleum oils or liquid hydrocarbons [7] was curve-fitted to the Coolanol 25R and PAO data. The equation is of the form

$$\nu = [10^{(10^A/T^B)} - C] \times 10^{-6} \quad (2)$$

In Eq. (2), the kinematic viscosity (ν) is in m^2/s and the temperature (T) is in K. The curve-fitted constants A , B , and C to be used in Eq. (2) for Coolanol 25R (C25R) and PAO are also tabulated in Table 1. The curve-fitted equation for ν pre-

Table 1 Curve-fitted constants for density, specific heat, thermal conductivity, and kinematic viscosity equations

| Property | Fluid | A | B | C | D | E | F |
|----------|-------|--------------------|------------------------|------------------------|-------------------------|------------------------|--------------------------|
| ρ | C25R | 1.13×10^3 | –0.784 | | | | |
| | PAO | 1.36×10^3 | –4.56 | 0.0157 | -0.280×10^{-4} | 0.174×10^{-7} | |
| c_p | C25R | 0.492 | 4.49×10^{-3} | | | | |
| | PAO | 1.022 | 3.77×10^{-3} | | | | |
| k | C25R | 0.453 | -4.64×10^{-3} | 0.275×10^{-4} | -0.809×10^{-7} | 0.117×10^{-9} | -0.667×10^{-13} |
| | PAO | 0.154 | -5.88×10^{-5} | | | | |
| ν | C25R | 8.36 | 3.408 | 0.802 | | | |
| | PAO | 9.67 | 3.923 | 0.700 | | | |

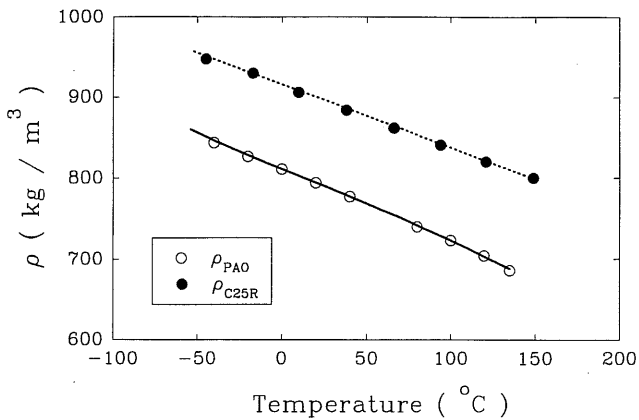


Figure 1 Variation of density with temperature for PAO and Coolanol 25R.

dicts the 13 Coolanol 25R data points with a maximum deviation of +5.5% and an average absolute deviation of 1.9%. For the 13 PAO data points the maximum deviation was +3.4% with an average absolute deviation of 1.3%.

The variation of ρ , c_p , k , and ν with temperature for Coolanol 25R (C25R) and PAO over the temperature range from -54 to 135°C are compared in Figures 1–4, respectively. Another thermophysical property that plays an important role in the hydraulic and thermal performance of coolants is absolute viscosity (μ). The variation of μ with temperature for the two fluids is shown in Figure 5. The values of μ were determined from the product of density and kinematic viscosity values.

The expressions and the constants for the thermophysical properties presented in this section were also programmed. The interactive computer program produces thermophysical properties for Coolanol 25R or PAO at any temperature in the

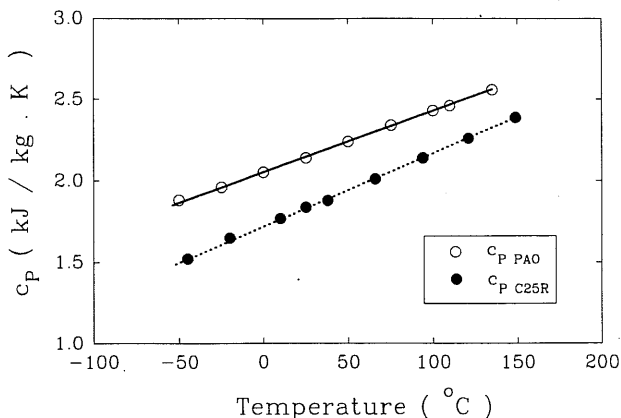


Figure 2 Variation of specific heat with temperature for PAO and Coolanol 25R.

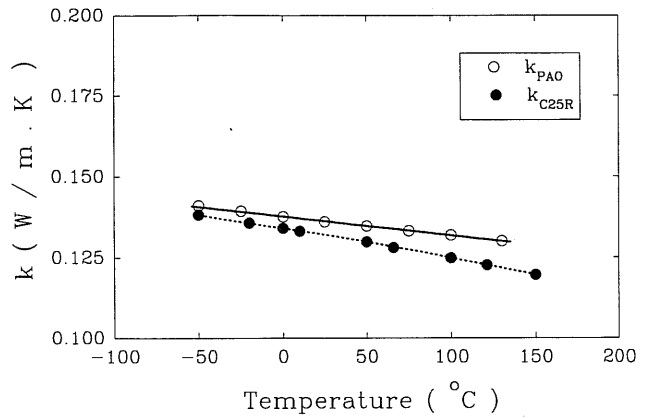


Figure 3 Variation of thermal conductivity with temperature for PAO and Coolanol 25R.

range from -54 to 135°C , in either SI or English units. Single or multipoint calculations can be performed. The tabulated results can be viewed on the screen and/or stored into a specified data file [8].

HEAT TRANSFER PARAMETER

From a heat transfer viewpoint, coolants are rated by first considering the applicable correlating equation. Considering a problem of heat transfer in forced convection to a fluid in a duct or channel, the form of the correlation is

$$\text{Nu} = C \text{Re}^m \text{Pr}^n \quad (3)$$

where m is near 0.5 for laminar flow and 0.8 for turbulent flow and n is approximately 0.4 for heating in both flow regimes. The exact values of C , m , and n are flow regime and configuration

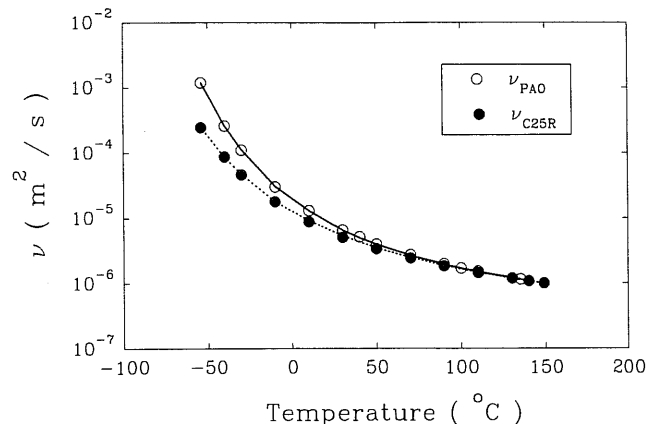


Figure 4 Variation of kinematic viscosity with temperature for PAO and Coolanol 25R.

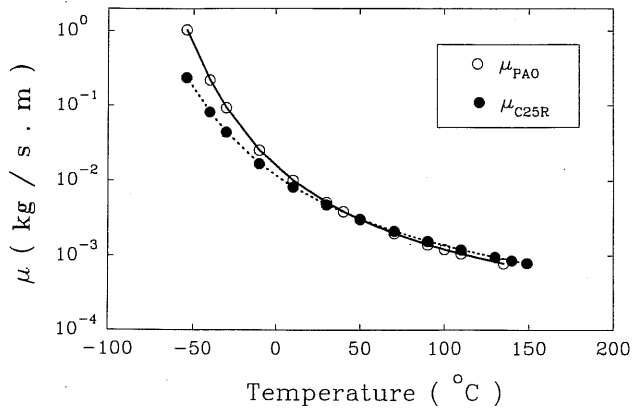


Figure 5 Variation of absolute viscosity with temperature for PAO and Coolanol 25R.

dependent and should be obtained experimentally. It is to be noted that although Eq. (3) offers the most convenient relation for heat transfer in a duct or channel, the analysis presented in this section can be easily applied to more complex situations where the heat transfer coefficient is influenced by the duct or channel length and natural-convection effects. Kakac and co-workers [9] provide several empirical heat transfer correlations for these and other complex situations.

Substituting the definitions for Nusselt number ($Nu = hD/k$), Reynolds number ($Re = \rho VD/\mu$), and Prandtl number ($Pr = \mu c_p/k$) in Eq. (3) and solving for the heat transfer coefficient h ,

$$h = C \frac{k}{D} \left(\frac{\rho VD}{\mu} \right)^m \left(\frac{\mu c_p}{k} \right)^n \quad (4)$$

Applying Eq. (4) to the two fluids under consideration, Coolanol 25R and PAO, assuming that the two fluids are running through two passages of identical equivalent diameters and at identical velocities, we divide and rearrange the resulting equations to obtain

$$\frac{h_{PAO}}{h_{C25R}} = \frac{\left(\rho^m k^{1-n} c_p^n / \mu^{m-n} \right)_{PAO}}{\left(\rho^m k^{1-n} c_p^n / \mu^{m-n} \right)_{C25R}} \quad (5)$$

Equation (5) indicates that heat transfer coefficient can be represented in terms of a dimensional grouping of fluid properties ρ , c_p , k , and μ . The properties contained in the grouping are definite functions of temperature.

Generalizing the results of Eq. (5) by setting $a = m$, $b = 1 - n$, $c = n$, and $d = m - n$ and

introducing the term heat transfer parameter (HTP) defined as,

$$HTP = \rho^a k^b c_p^c / \mu^d \quad (6)$$

which can be used as a rating criterion for heat transfer fluids. The heat transfer parameter is not dimensionless; therefore, its numerical value depends on the units used. The same units must be used in computing values for each coolant that is to be compared.

Equation (6) indicates that there is a way of comparing heat transfer properties of fluids on the basis of temperature (from values of ρ , c_p , k , and μ), configuration, and flow regime (values of exponents a , b , c , and d).

For typical values of m and n for laminar forced convection ($m = 0.5$, $n = 0.4$) and turbulent forced convection ($m = 0.8$, $n = 0.4$) in internal flows, the specific form of the heat transfer parameter for each flow regime becomes

$$HTPL = \rho^{0.5} k^{0.6} c_p^{0.4} / \mu^{0.1} \quad (7)$$

$$HTPT = \rho^{0.8} k^{0.6} c_p^{0.4} / \mu^{0.4} \quad (8)$$

where HTPL and HTPT designate the laminar and turbulent heat transfer parameters, respectively.

We apply Eq. (7) or (8) to Eq. (5) to obtain an expression for the ratio of PAO-to-Coolanol 25R heat transfer coefficients in terms of the heat transfer parameter. Figure 6 shows the variation of PAO-to-C25R heat transfer parameter ratio with temperature for laminar and turbulent flow regimes. The figure indicates that there could be a substantial difference between the heat transfer properties of the two fluids. This difference depends on the coolant flow regime and the coolant

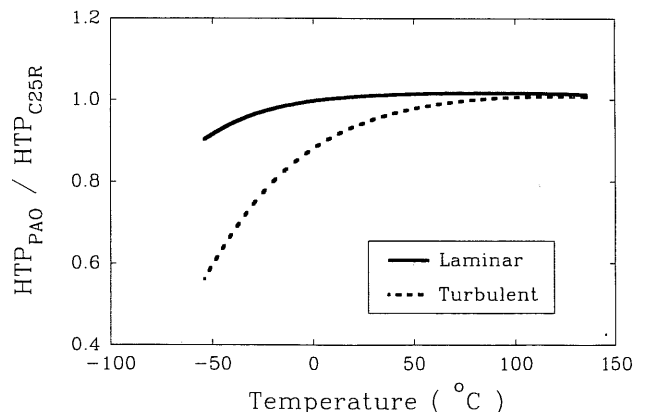


Figure 6 Variation of PAO-to-C25R heat transfer parameter ratio with temperature (laminar and turbulent flows).

operating temperature. In the laminar flow regime (see the solid line in Figure 6) and at the lowest coolant temperature (-54°C), the heat transfer parameter for PAO is about 11% lower than that of Coolanol 25R; this difference diminishes to about 2% at -14°C . At temperatures above -14°C , there is virtually no difference in the heat transfer properties of the two fluids. However, in turbulent flow, the differences are much larger and are sustained over a larger temperature range. Referring to the dashed line in Figure 6, at -54°C the heat transfer parameter for PAO is about 78% lower than that of Coolanol 25R. This difference reduces to about 21% at -14°C and to about 2% at 56°C . Beyond this temperature, the two fluids behave the same way.

Overall, from a heat transfer view point, Coolanol 25R outperforms PAO in the low-temperature region in both flow regimes. The difference is substantial for turbulent flow in the temperature range from -54°C to about 6°C . Therefore, at these low temperatures, in order for the heat transfer characteristics of the systems operating with PAO to be fairly comparable with the Coolanol 25R systems, operation in the laminar flow regime is recommended. The type of analysis presented here indicates how it can be established which fluid has the better heat transfer properties.

HYDRAULIC PERFORMANCE

Comparison of hydraulic performance of Coolanol 25R and PAO is based on the relationship between pressure drop and flow rate. The Moody diagram [10] establishes the proper normalized dimensionless pressure drop parameter [$f = \Delta P / (L/D)(1/2\rho V^2)$] and flow parameter ($\text{Re} = \rho VD / \mu$) for a round pipe with a fixed relative roughness in the form

$$f = \phi_1(\text{Re}) \quad (9)$$

where ϕ_1 is a function to be determined experimentally or analytically. Therefore, when data are plotted as f versus Re , usually a log-log plot, they fall on a single curve for a constant value of relative roughness.

The major difficulty in application of Eq. (9) to an avionics system is associated with the proper evaluation of diameter (D) and fluid velocity (V) in the definitions of f and Re . The coolant flow

loop for an avionics system (e.g., radar transmitter) is very different than for a long, straight, round pipe. In the coolant flow loop there are numerous bends, sudden expansions and contractions, change of flow areas, noncircular flow passages, and other local obstructions, the combined effect of which results in the overall pressure drop of the system. Therefore, the diameter (D) appearing in the definitions of f and Re must represent these effects. However, for a given system each of these local effective diameters is a constant, and consequently their combined influence can be included as a constant in the function ϕ_1 of Eq. (9). The fluid velocity (V) appearing in the definitions of f and Re must also be representative of the various local velocities within the system, due to the existence of numerous different flow areas, and hence different velocities in the system. However, the velocity at any given point in the system differs from the volume flow rate (\dot{Q}) only by the local flow area, which is considered constant. Therefore, V can be replaced by \dot{Q} , and the local invariant flow areas can be included as constants in the function ϕ_1 of Eq. (9).

Based on the above discussion, the definitions of f and Re and Eq. (9) can be rearranged in the form

$$P = \phi_2(F) \quad (10)$$

where $P = \Delta P / \rho \dot{Q}^2$ and $F = \dot{Q} / \nu$ are the new normalized dimensional pressure drop and flow parameters, respectively. It should be realized that Eq. (10) is a dimensional equation, and that the function ϕ_2 (which must be determined experimentally) is different for each system. This is in sharp contrast to the function ϕ_1 in Eq. (9) for a circular pipe flow, where the same function applies to all round pipes with a fixed relative roughness.

A simple form of the function ϕ_2 in Eq. (10) can be determined for low and high values of Reynolds number by inspection of the Moody diagram [10]. For low Re values (laminar flow), f versus Re is a straight line with slope of -1 . For high Re values (complete turbulence), f versus Re for a given relative roughness is a straight line with a slope of 0.

The new dimensional parameters P and F differ from the Moody dimensionless parameters f and Re only by an unknown constant at each location in the system. Therefore, the following equation should represent the functional form

(ϕ_2) that exists between P and F for low and high Reynolds numbers:

$$P = A + B/F \quad (11)$$

where A and B are experimentally determined constants for a given system.

A plot of Eq. (11) for a hypothetical situation is shown as Fig. 7. This figure is a log-log plot of pressure drop parameter (P) and flow parameter (F). The plot exhibits a slope of -1 at low values of F ($P \approx B/F$) and approaches a slope of 0 at high values of F ($P \approx A$). These terminal slopes are indicative of fully laminar flow at low values of F and fully turbulent flow at high values of F and are comparable with the Moody diagram. It should be realized that the constants A and B in Eq. (11) are unique for a given system but are independent of the type of fluid used in the system. This allows for generalization of the hydraulic performance of the system for the two limiting cases of Eq. (11). These limiting cases are referred to as the fully laminar and fully turbulent and will be discussed next.

Fully Laminar Case

For the fully laminar case, Eq. (11) can be approximated by $P = B/F$. Using the definitions of P and F and solving for ΔP results in

$$\Delta P = B\mu\dot{Q} \quad (12)$$

Equation (12) implies that the pressure drop and volume flow rate depend strongly on the absolute viscosity of the heat transfer fluid. We apply Eq.

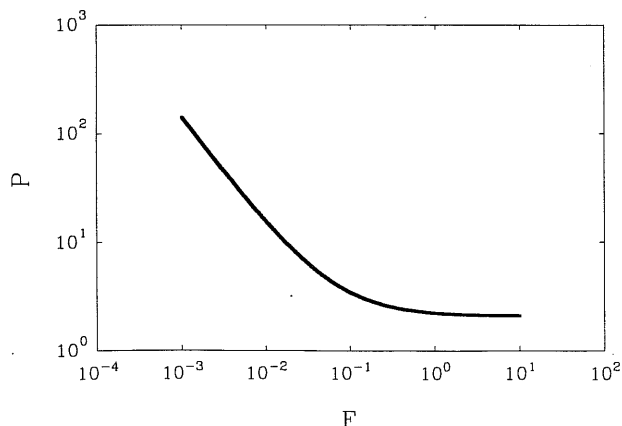


Figure 7 Functional form between pressure drop parameter and flow parameter for a hypothetical situation.

(12) to the two fluids under consideration, Coolanol 25R and PAO, assuming the two fluids are running through two identical systems at identical coolant volume flow rates. We then divide the resulting equations to obtain

$$\frac{\Delta P_{\text{PAO}}}{\Delta P_{\text{C25R}}} = \frac{\mu_{\text{PAO}}}{\mu_{\text{C25R}}} \quad (13)$$

An equation similar to Eq. (13) can be developed for the volume flow rate ratio of the two fluids, assuming identical systems at identical pressure drops. The resulting equation is

$$\frac{\dot{Q}_{\text{PAO}}}{\dot{Q}_{\text{C25R}}} = \frac{\mu_{\text{C25R}}}{\mu_{\text{PAO}}} \quad (14)$$

The variations of PAO-to-C25R pressure drop and volume flow rate ratios with coolant temperature are shown in Figure 8 by the solid and broken lines, respectively. The figure indicates that the ratios vary dramatically in the temperature range from -54 to 26°C . At these low temperatures, the pressure drop ratio varies from about 1 at 26°C to about 4.4 at -54°C . This fourfold increase in the pressure drop is due to the much higher absolute viscosity of PAO at these low temperatures (see Figure 5). At temperatures warmer than 26°C , the pressure drop variation with temperature is relatively small and approaches unity at 46°C . At temperatures greater than 46°C , the pressure drop ratio drops below unity, indicating that the system with Coolanol 25R as the working fluid experiences higher pressure drop than the system with PAO at identical operating conditions. The pressure drop difference increases with temperature, and at the highest temperature of 135°C , it reaches a value of about 16%.

The variation of volume flow rate ratio with coolant temperature, shown by the broken line in Figure 8, demonstrates a trend similar but opposite to the pressure drop ratio. At low temperatures, the volume flow rate of PAO is much smaller than that of Coolanol 25R for the same operating conditions and pressure drop. This difference decreases with increasing temperature, and the ratio approaches unity around 46°C . At temperatures greater than 46°C , the volume flow rate ratio goes above unity, indicating that, for the same operating conditions, the Coolanol 25R volume flow rate is lower in comparison to PAO.

The observations made about the variation of PAO-to-C25R pressure drop and volume flow rate

$$\frac{\dot{Q}_{\text{PAO}}}{\dot{Q}_{\text{C25R}}} = \left(\frac{\rho_{\text{C25R}}}{\rho_{\text{PAO}}} \right)^{1/2} \quad (17)$$

The variations of PAO-to-C25R pressure drop and volume flow rate ratios with coolant temperature are shown in Figure 9 by the solid and broken lines, respectively. The figure indicates that there is a modest variation in the ratios with respect to temperature. The PAO pressure drop at the lowest temperature of -54°C is about 11% lower than that of Coolanol 25R at comparable conditions. This pressure drop difference increases with temperature and reaches about 18% at 135°C . This behavior is due to the lower value of PAO density and the fact that the difference between densities of the two fluids increases with an increase in temperature (see Figure 1).

The variation of volume flow rate ratio with temperature shown in Figure 9 by the broken line indicates that at the low end of the temperature range (-54°C), the volume flow rate of PAO is about 6% higher than that of Coolanol 25R for the same operating conditions and pressure drop. As the coolant temperature increases to 135°C , this difference increases to about 9%.

From a hydraulic performance viewpoint, it appears that for the case of fully turbulent flow, replacement of Coolanol 25R with PAO would be advantageous with respect to the system pressure drop and coolant flow rate over the entire temperature range of operation.

In practice, the results of Figures 8 and 9 for fully laminar and turbulent flows are not applicable over the entire temperature range of operation. Laminar flow (low flow rate), typically occurs

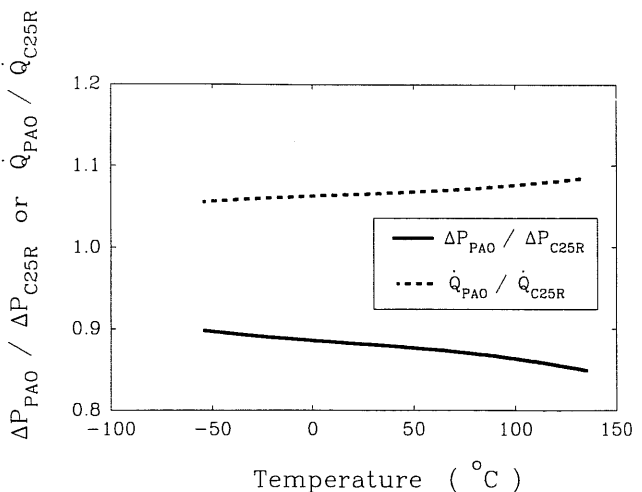


Figure 9 Variation of PAO-to-C25R pressure drop and volume flow rate ratios with temperature (fully turbulent case).

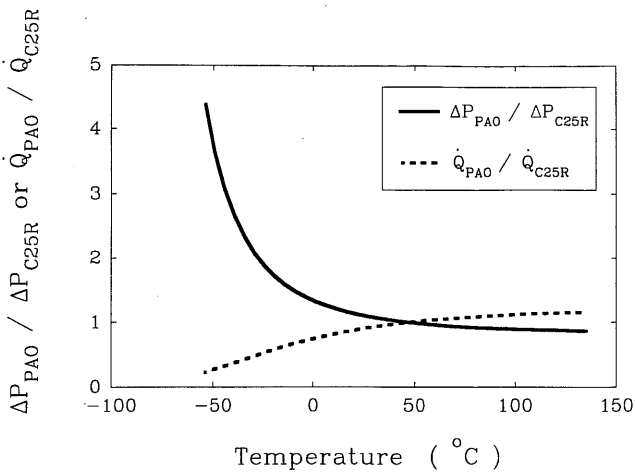


Figure 8 Variation of PAO-to-C25R pressure drop and volume flow rate ratios with temperature (fully laminar case).

ratios in the laminar flow region should be put in the context of the overall system operation. The higher pressure drop associated with PAO at low temperatures ($< 26^{\circ}\text{C}$) means that, when replacing Coolanol 25R with PAO, the system pump must be capable of handling the additional losses at these low temperatures. The low volume flow rate of PAO at low temperatures may not be adequate to satisfy the cooling requirements of the electronic equipment. However, replacement of Coolanol 25R with PAO, from the standpoint of hydraulic performance, appears to be advantageous when operating in the laminar flow regime at temperatures above 46°C .

Fully Turbulent Case

For the fully turbulent case, Eq. (11) can be approximated by $P = A$. Using the definitions of P and F and solving for ΔP results in

$$\Delta P = A \rho \dot{Q}^2 \quad (15)$$

Equation (15) implies that the pressure drop and volume flow rate depend strongly on the density of the heat transfer fluid. We apply Eq. (15) to the two fluids under consideration and follow the same assumptions and procedures outlined for the previous case. The resulting equations for the pressure drop and volume flow rate ratios of PAO to C25R are

$$\frac{\Delta P_{\text{PAO}}}{\Delta P_{\text{C25R}}} = \frac{\rho_{\text{PAO}}}{\rho_{\text{C25R}}} \quad (16)$$

when low-temperature (high-viscosity) liquid is used. Therefore, Figure 8 results are recommended for temperatures at or below 0°C. At these low temperatures, the absolute viscosity of the coolant strongly influences the pressure drop and the volume flow rate of the system, causing the system with PAO to experience higher pressure drop and low volume flow rates. Turbulent flows (high flow rate) are typically associated with the use of warmer liquid coolant (low viscosity). In this case, Figure 9 results are recommended for temperatures at or above 100°C. At these high temperatures, the density of the coolant strongly influences the magnitude of the system pressure drop and volume flow rate. The system with PAO at these temperatures performs better than the Coolanol 25R system.

In the intermediate temperature range from 0 to 100°C, the flow might not be either fully laminar or fully turbulent, and the use of Figure 8 or 9 might be questionable. In this temperature range, the pressure drop and the volume flow rate depend on both the density and the absolute viscosity of the coolant. However, the viscosity difference between PAO and Coolanol 25R is less extreme (see Figure 5), and the lower density of PAO (see Figure 1) has more influence on the PAO-to-C25R pressure drop and volume flow rate ratios, tending to counteract the influence of higher absolute viscosity. The end result would be ratios close to unity. Therefore, at these temperatures the hydraulic performance of the PAO and Coolanol 25R systems should be nearly comparable.

THERMAL PERFORMANCE

One of the major objectives in the thermal analysis of an electronic box (e.g., radar transmitter) is the determination of the component hot-spot surface temperature. This temperature is determined by adding all of the temperature rises along the heat flow path to the inlet temperature of the coolant. For the thermal performance analysis, assuming identical systems with the exception of the liquid coolant, only the liquid-coolant contributions to the component surface temperature were considered. Temperature rises across the interface or in solids were ignored in this analysis. The liquid coolant contributes in two ways to the component surface temperature: (1) temperature rise due to the heat input from the electronics to the coolant as it flows through the electronic box,

ΔTC ; and (2) temperature rise due to the thermal resistance across the liquid coolant thermal boundary layer from the surface of the component to the coolant, ΔTBL . The basic forced liquid flow relationships needed for determination of these temperature rises will be presented next [11, 12].

The temperature rise in a liquid cooled system can be determined from

$$\Delta TC = \dot{q} / (\rho c_p) \dot{Q} \quad (18)$$

where ΔTC is the coolant temperature rise, \dot{q} is the power dissipation, \dot{Q} is the volume flow rate of coolant, and (ρc_p) is the thermal capacitance of the coolant.

In a forced liquid system, a thermal boundary layer develops and clings to the heat transfer surface and restricts the flow of heat from the electronic components to the liquid coolant. The temperature rise across the thermal boundary layer (ΔTBL) then becomes

$$\Delta TBL = \dot{q} / hA \quad (19)$$

where \dot{q} is the power dissipation, h is the forced-convection heat transfer coefficient, and A is the component surface area.

The influence of different coolants (Coolanol 25R and PAO) and flow regimes (laminar and turbulent) on the temperature rises obtained from Eqs. (18) and (19) will be discussed next.

Liquid-Coolant Temperature Rise

Applying Eq. (18) to the two fluids under consideration, assuming two identical systems at identical power dissipations and coolant volume flow rates, and dividing the resulting equations, we obtain

$$\frac{\Delta TC_{PAO}}{\Delta TC_{C25R}} = \frac{(\rho c_p)_{C25R}}{(\rho c_p)_{PAO}} \quad (20)$$

An equation identical to Eq. (20) can be developed for the volume flow rate ratio of the two fluids, assuming identical systems at identical power dissipation and coolant temperature rises. The resulting equation is

$$\frac{\dot{Q}_{PAO}}{\dot{Q}_{C25R}} = \frac{(\rho c_p)_{C25R}}{(\rho c_p)_{PAO}} \quad (21)$$

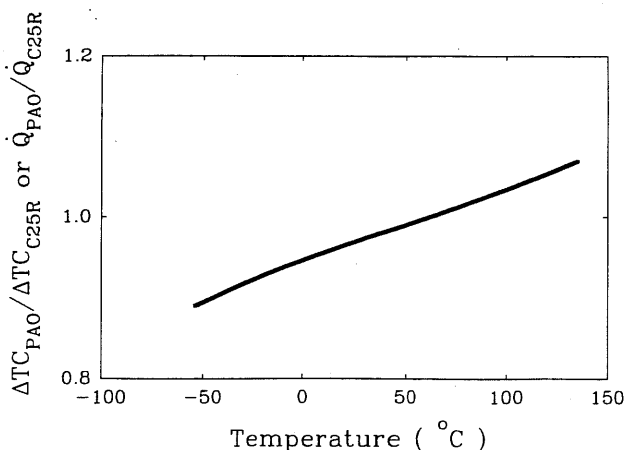


Figure 10 Variation of PAO-to-C25R coolant temperature rise and volume flow rate ratios with temperature.

Comparison of Eqs. (20) and (21) shows that the PAO-to-C25R coolant temperature rise and volume flow rate ratios are directly proportional to the C25R-to-PAO thermal capacitance ratio. The variation of ratios given in Eqs. (20) and (21) with coolant temperature are shown in Figure 10. The results of this figure can be better understood by examining Figure 11, which shows the variation of thermal capacitance with temperature for the two fluids. The figures indicate that, due to the higher thermal capacitance of PAO at temperatures below 61°C, the coolant temperature rise is lower than that of Coolanol 25R at the same coolant flow rate. The maximum difference is about 12% at the lowest temperature of -54°C. Therefore, for temperatures below 61°C, the contribution from coolant temperature rise to the component surface temperature would be smaller using PAO as opposed to Coolanol 25R, assuming the same coolant flow rates. For coolant temperatures above

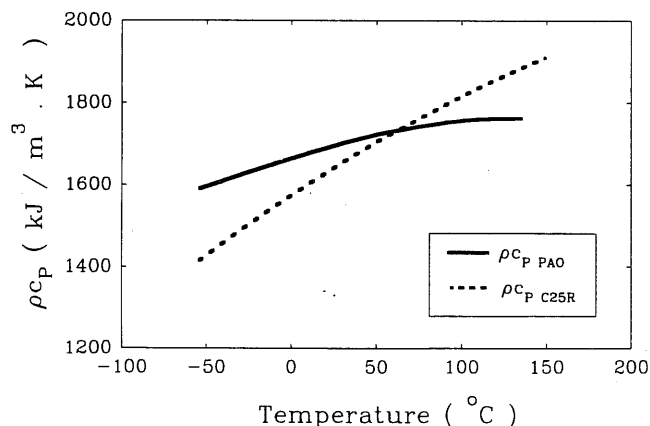


Figure 11 Variation of thermal capacitance with temperature for PAO and Coolanol 25R.

61°C, the reverse is true. The Coolanol 25R temperature rise is lower than that of PAO. The difference reaches a maximum of about 7% at 135°C.

The results presented in Figure 10 can also be interpreted as the variation of PAO-to-C25R volume flow rate ratio with temperature for the same coolant temperature rise. As indicated, at the lowest temperature of -54°C, in order to have the same coolant temperature rise for the two fluids, the volume flow rate of PAO should be about 1.12 times greater than that of Coolanol 25R. This is in sharp contrast with the hydraulic analysis results at the same temperature (see Figure 8). At -54°C, for comparable pressure drop in the system for the two fluids, the volume flow rate of PAO can be about 4.4 times that of Coolanol 25R.

Thermal Boundary-Layer Temperature Rise

Applying Eq. (19) to the two fluids under consideration, assuming two identical systems at identical power dissipations and volume flow rates, and dividing the resulting equations, we obtain

$$\frac{\Delta TBL_{PAO}}{\Delta TBL_{C25R}} = \frac{h_{C25R}}{h_{PAO}} \quad (22)$$

It was shown earlier that the forced-convection heat transfer coefficient can be represented in terms of a dimensional grouping of fluid heat transfer properties called heat transfer parameter (HTP); see Eqs. (5) and (6). Introducing Eq. (6) into Eq. (22) results in

$$\frac{\Delta TBL_{PAO}}{\Delta TBL_{C25R}} = \frac{HTP_{C25R}}{HTP_{PAO}} \quad (23)$$

where the specific expressions for laminar and turbulent forced convection are given by Eqs. (7) and (8), respectively.

The variation of PAO-to-C25R thermal boundary-layer temperature rise ratio with temperature is shown in Figure 12. The results indicate that at low temperatures in the turbulent flow regime, there is a substantial difference in the thermal boundary-layer temperature rise ratio. As shown, the thermal boundary-layer temperature rise at low temperatures for both flow regimes is smaller when Coolanol 25R is used in comparison to PAO. This is due to the better heat transfer

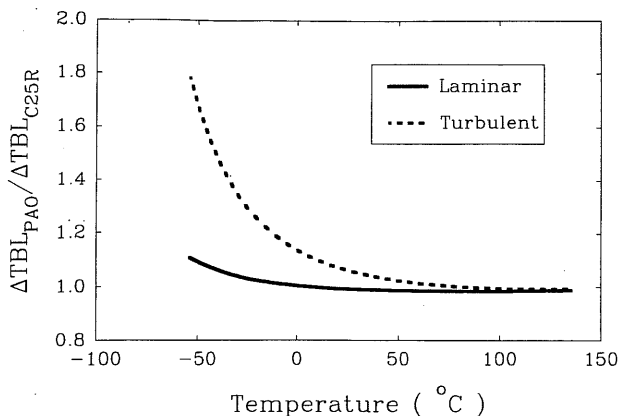


Figure 12 Variation of PAO-to-C25R thermal boundary-layer temperature-rise ratio with temperature (laminar and turbulent flows).

properties of Coolanol 25R; see Figure 6. The thermal boundary-layer temperature rise for PAO at -54°C is about 11% for laminar flow and increases to about 78% for turbulent flow. The difference between the two fluids diminishes at about -14°C for laminar flow and at around 56°C for turbulent flow. Therefore, for the systems operating with PAO in the turbulent flow regime and at low temperatures (-54 to 6°C), the contribution of the temperature rise across the liquid-coolant thermal boundary layer to the component surface temperature could be substantially higher than for the systems using Coolanol 25R for the same conditions. Based on these observations, the flow should be in the laminar regime for a comparable thermal boundary-layer temperature rise between the two fluids in the low-temperature regions.

Combined Temperature Rise

In order to determine the collective contributions of the liquid coolant to the component surface temperature, temperature rises expressed by Eqs. (18) and (19) should be added together. This combined temperature rise (ΔT) is given by

$$\Delta T = \Delta TC + \Delta TBL = \frac{\dot{q}}{(\rho c_p)\dot{Q}} + \frac{\dot{q}}{hA} \quad (24)$$

Applying Eq. (24) to the two fluids under consideration, assuming two identical systems at identical power dissipations and coolant flow rates, and

dividing and rearranging the resulting equations, we obtain

$$\frac{\Delta T_{\text{PAO}}}{\Delta T_{\text{C25R}}} = \frac{[(\rho c_p)_{\text{C25R}}/(\rho c_p)_{\text{PAO}}] + (\dot{Q}_{\text{C25R}}/A)[(\rho c_p)_{\text{C25R}}/h_{\text{PAO}}]}{1 + (\dot{Q}_{\text{C25R}}/A)[(\rho c_p)_{\text{C25R}}/h_{\text{C25R}}]} \quad (25)$$

where the forced-convection heat transfer coefficient for the laminar or turbulent flow is represented by Eq. (4). Determination of the variation of the PAO-to-C25R combined temperature-rise ratio with temperature requires specific information on a given system, such as volume flow rate, component surface area, forced-convective heat transfer coefficient, etc. However, a comparison between the relative magnitudes of the combined temperature-rise ratios for the two fluids under consideration can be made by considering the two limiting cases of Eq. (25). For very low flow rates (fully laminar flow), Eq. (25) can be approximated by

$$\frac{\Delta T_{\text{PAO}}}{\Delta T_{\text{C25R}}} = \frac{(\rho c_p)_{\text{C25R}}}{(\rho c_p)_{\text{PAO}}} \quad (26)$$

Similarly, for very high flow rates (fully turbulent flow), Eq. (25) can be approximated by

$$\frac{\Delta T_{\text{PAO}}}{\Delta T_{\text{C25R}}} = \frac{h_{\text{C25R}}}{h_{\text{PAO}}} \quad (27)$$

It was shown earlier that, the heat transfer coefficient for turbulent forced convection can be represented in terms of a dimensional grouping of fluid heat transfer properties called turbulent heat transfer parameter (HTPT); see Eqs. (5), (6), and (8). Introducing Eq. (8) into Eq. (27) results in

$$\frac{\Delta T_{\text{PAO}}}{\Delta T_{\text{C25R}}} = \frac{\text{HTPT}_{\text{C25R}}}{\text{HTPT}_{\text{PAO}}} \quad (28)$$

The variation of Eqs. (26) and (28) with temperature is shown in Figure 13 for both flow regimes. In the laminar flow regime, the net effect of the two temperature rises on the component surface temperature for the two fluids is about the same. In the temperature range from -54 to 61°C , the component surface temperature for the system with PAO would be lower than for the system with Coolanol 25R by as much as 11%. This is due primarily to the fact that, in this region, the higher thermal capacitance of PAO (see Figure 11), ex-

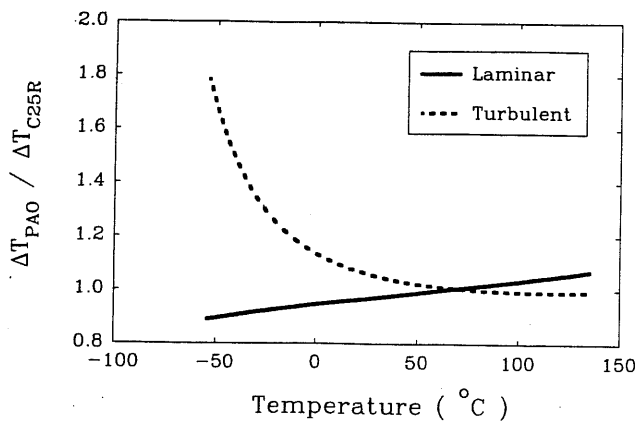


Figure 13 Variation of PAO-to-C25R combined temperature-rise ratio with temperature (fully laminar and fully turbulent cases).

ceeds its lower heat transfer properties (see Figure 6). For temperatures greater than 61°C, the component surface temperature with Coolanol 25R would be lower than for the system with PAO by as much as 7%. Therefore, in the low-temperature regions with laminar flow regime, use of PAO in comparison to Coolanol 25R is preferred.

In the turbulent flow regime, the net effect of the two temperature rises on the component surface temperature for the two fluids is substantially different in the low-temperature region. In the temperature range from -54 to -61°C, the lower coolant-temperature rises with PAO (due to the higher thermal capacitance of PAO) cannot offset the much larger temperature rises across the thermal boundary layer (due to the much lower heat transfer properties of PAO). For example, at the lowest temperature of -54°C, the combined temperature rise with PAO as the cooling fluid is higher than for the system with Coolanol 25R as the coolant at comparable conditions by as much as 78%. This difference drops to about 21% at -14°C and to less than 10% for temperatures above 11°C. The difference is almost negligible for temperatures above 61°C. Therefore, in the low-temperature regions with turbulent flow regime, use of PAO over Coolanol 25R for the same operating conditions is not advisable from a thermal performance viewpoint.

It is to be emphasized that the results presented in Figure 13, based on Eqs. (26) and (28) for fully laminar and turbulent flows, represent the two limiting cases of the general equation, Eq. (25). For a particular avionics system, depending on the specifics of the system (i.e., volume flow rate, component surface area, forced-convection heat transfer coefficient, etc.), the PAO-to-C25R

combined temperature-rise ratios fall somewhere between the two limiting cases.

Coolant Thermal Time Constant

In the thermal performance analysis presented so far, steady-state operation was assumed. In order to determine how long it would take for the coolant to reach a specified steady-state temperature, we introduce the concept of a thermal time constant (τ), which for the coolant alone is the product of the coolant thermal resistance and the coolant thermal capacitance, as shown in Eq. (29),

$$\tau = \left(\frac{1}{hA} \right) (\rho c_p V) = \left(\frac{\rho c_p}{h} \right) L_c \quad (29)$$

where the volume-to-area ratio (V/A) is the characteristic length (L_c) for the system. Determination of the actual value of the thermal time constant for the coolant requires specific information on a given system. However, a comparison between the relative magnitudes of the thermal time constants for the two fluids under consideration can be made.

Applying Eq. (29) to PAO and Coolanol 25R, assuming the two fluids are running through two identical systems with identical velocities and characteristic lengths, we divide the resulting equations to obtain

$$\frac{\tau_{\text{PAO}}}{\tau_{\text{C25R}}} = \frac{(\rho c_p)_{\text{PAO}} (\text{HTP}_{\text{C25R}})}{(\rho c_p)_{\text{C25R}} (\text{HTP}_{\text{PAO}})} \quad (30)$$

where, as before, the heat transfer coefficient (h) has been replaced with the heat transfer parameter (HTP).

The variation of PAO-to-C25R thermal time-constant ratio with temperature is shown in Figure 14 for both flow regimes. In the laminar flow regime, due to larger resistance in the heat flow path for PAO, its thermal time constant is longer than that of Coolanol 25R by as much as 25% at -54°C. This difference quickly reduces with an increase in the coolant temperature. At about 41°C, the two fluids have identical thermal time constants. At temperatures above 41°C, the thermal time constant for Coolanol 25R exceeds that of PAO, and it reaches a maximum difference of about 8% at 135°C.

In the turbulent flow regime, the difference between the thermal time constants of the two

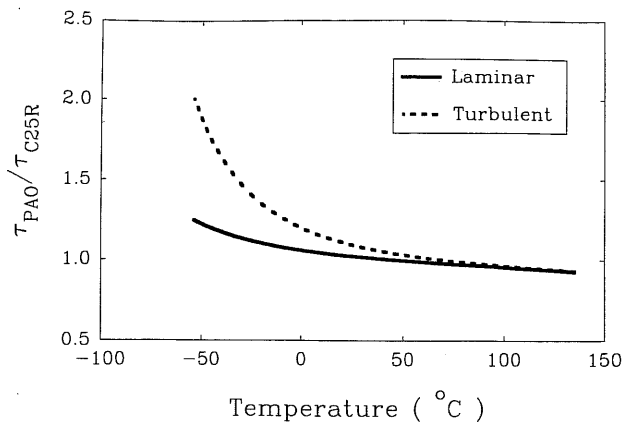


Figure 14 Variation of PAO-to-C25R thermal time constant ratio with temperature (laminar and turbulent flows).

fluids in the low-temperature region is even more pronounced. At -54°C , the PAO thermal time constant is longer by a factor of 2 than that of Coolanol 25R. This difference slowly reduces with an increase in the coolant temperature. At about 66°C , the two fluids have identical thermal time constants. For temperatures above 66°C , the behavior is almost identical to that for the laminar flow regime.

Considering the laminar and turbulent flow thermal time-constant ratios given in Figure 14, it appears that, in the low-temperature region with PAO as the coolant, it would take longer to obtain a prescribed steady-state temperature in comparison to a system with Coolanol 25R as the coolant. The delay time becomes much longer for turbulent flow operation. Therefore, to minimize the thermal time-constant differences between the two fluids in the low-temperature regions, it is recommended that the PAO system operate in the laminar flow regime.

CONCLUSIONS

The simple methodology and the general expressions offered in this study provide the means by which the hydraulic and thermal performance of different heat transfer fluids, running through identical systems, can be compared with another. The results for the hydraulic performance of PAO versus Coolanol 25R indicate that at low temperatures (below 0°C) and in laminar flow regime (low flow rate), PAO, due to its large pressure drop and/or low volume flow rate, is not at all compatible with Coolanol 25R. However, for temperatures above 26°C , the performance of PAO is as good or better than that of Coolanol 25R. In the

turbulent region, the hydraulic performance of PAO is better than that of Coolanol 25R over the entire reported temperature range (-54 to 135°C).

The comparison of the thermal performance of the two coolants in the laminar region showed much closer agreement. The thermal performance of PAO for temperatures below 61°C would be slightly better than Coolanol 25R. However, in the turbulent region for temperatures below 61°C , Coolanol 25R outperforms PAO. The difference is substantial at temperatures below -14°C .

For comparable hydraulic and thermal performance of the two coolants, the flow must be laminar at low temperatures (below 0°C) when using PAO. In addition, to overcome the high pressure drop associated with PAO, the liquid cooling system pump must be larger in comparison to that for the Coolanol 25R system. For temperatures above 0°C , the overall performance of the two coolants is reasonably close and fairly independent of the flow regime.

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NOMENCLATURE

| | |
|-------|---|
| A | component surface area |
| c_p | specific heat at constant pressure |
| D | passage diameter |
| f | Moody friction factor ($= \Delta PD / 2L\rho V^2$) |
| F | normalized dimensional flow parameter ($= \dot{Q} / \nu$) |
| h | forced-convection heat transfer coefficient |
| HTP | heat transfer parameter defined in Eq. (6) |
| HTPL | heat transfer parameter for laminar flow defined in Eq. (7) |
| HTPT | heat transfer parameter for turbulent flow defined in Eq. (8) |
| k | thermal conductivity |
| L | passage length |
| L_c | characteristic length |

| | |
|-----------------|---|
| Nu | Nusselt number ($= hD/k$) |
| P | normalized dimensional pressure drop parameter ($= \Delta P/\rho\dot{Q}^2$) |
| Pr | Prandtl number ($= \mu c_p/k$) |
| \dot{q} | power dissipation |
| \dot{Q} | volume flow rate |
| Re | Reynolds number ($= \rho VD/\mu$) |
| T | temperature |
| V | volume |
| V | velocity |
| ΔP | pressure drop |
| ΔT | combined temperature rise defined in Eq. (24) |
| ΔT_{BL} | thermal boundary-layer temperature rise defined in Eq. (19) |
| ΔT_C | liquid coolant temperature rise defined in Eq. (18) |
| μ | absolute viscosity |
| ν | kinematic viscosity |
| ρ | density |
| τ | thermal time constant |

Subscripts

| | |
|------|-----------------|
| C25R | Coolanol 25R |
| PAO | polyalphaolefin |

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