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Abstract

Blood, a valuable by-product of livestock slaughter, has numerous food, industrial, and pharmaceutical uses. Physical and rheological properties, including apparent viscosity, density, surface tension, thermal conductivity, and specific heat, are needed for the design of transport processes and by-product applications such as spray drying, blending, and extrusion. Information about these properties for slaughter by-products, however, is not currently available. Consequently, the objective of this study was to determine these properties for anticoagulated swine blood, blood plasma, and red blood cells between 5 and 35°C. The plasma in this study was enriched with hemoglobin from the red cells as a result of the rupture of red cells during frozen storage of the blood. These fluids all exhibited a pseudoplastic behavior which was affected by both shear rate and temperature; a nonlinear regression model which accounted for both factors was then determined for each fluid. In addition, these fluids all had density values 1.0 to 6.3% higher, and surface tension values 20.7 to 33.0% lower, than the respective values for water at temperatures between 5 and 35°C. Thermal conductivity results were 42.0 to 57.0% lower, and specific heat results were 9.0 to 17.4% lower, than the respective values for water at each temperature. Drying curves were also established for each fluid at drying temperatures of 80, 100, and 120°C

Keywords

livestock byproducts, blood, swine

Disciplines

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Comments

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PHYSICAL AND RHEOLOGICAL PROPERTIES OF SLAUGHTERHOUSE SWINE BLOOD AND BLOOD COMPONENTS

K. A. Rosentrater, R. A. Flores

ABSTRACT. *Blood, a valuable by-product of livestock slaughter, has numerous food, industrial, and pharmaceutical uses. Physical and rheological properties, including apparent viscosity, density, surface tension, thermal conductivity, and specific heat, are needed for the design of transport processes and by-product applications such as spray drying, blending, and extrusion. Information about these properties for slaughter by-products, however, is not currently available. Consequently, the objective of this study was to determine these properties for anticoagulated swine blood, blood plasma, and red blood cells between 5 and 35°C. The plasma in this study was enriched with hemoglobin from the red cells as a result of the rupture of red cells during frozen storage of the blood. These fluids all exhibited a pseudoplastic behavior which was affected by both shear rate and temperature; a nonlinear regression model which accounted for both factors was then determined for each fluid. In addition, these fluids all had density values 1.0 to 6.3% higher, and surface tension values 20.7 to 33.0% lower, than the respective values for water at temperatures between 5 and 35°C. Thermal conductivity results were 42.0 to 57.0% lower, and specific heat results were 9.0 to 17.4% lower, than the respective values for water at each temperature. Drying curves were also established for each fluid at drying temperatures of 80, 100, and 120°C.* **Keywords.** *Livestock byproducts, Blood, Swine.*

Agriculture produces tremendous quantities of waste materials. From 1991 to 1992, agribusinesses in Kansas alone produced over 72,000 t/yr of waste products and processing residues. Furthermore, over 58% (42,137 t/yr) of these agricultural wastes arose from livestock slaughter alone. Consequently, varied alternatives for waste disposal have been increasingly investigated, including incineration, composting, resale, and reuse as feed ingredients (Nelson and Flores, 1994).

In recent years, research has been conducted into alternative uses for blood collected from livestock slaughter to reduce contamination, eliminate waste, and produce value-added products. Because blood is a high quality protein source, blood and its components are becoming viable by-products of the slaughtering process (Wang et al., 1996). Shahidi et al. (1984) investigated the functional properties of beef blood globin, the protein in blood hemoglobin, and found that beef globin was 81.3% protein (d.b.). Hence, whole blood and red blood cells have gained popularity as a protein source for feed formulations

and pet foods (Donnelly et al., 1978; Shahidi et al., 1984). Wang et al. (1996) studied various mixtures of soy meal with either swine blood or swine red blood cells as potential ingredients for aquatic feeds. Cuperlovic et al. (1977) investigated the use of swine blood and tissue offals as a protein source for growing/finishing swine rations. Furthermore, livestock blood plasma exhibits excellent foaming, solubility, and emulsification properties, and is commonly incorporated into meat and confectionery products (Donnelly et al., 1978; Howell and Lawrie, 1983). In fact, beef blood plasma has been extensively used in the preparation of bologna and wieners (Caldironi and Ockerman, 1982).

Slaughterhouse blood and its components offer much potential as a protein source, not only for livestock feed formulations, but also for use in human food products and pharmaceuticals. To utilize these valuable by-products effectively, physical and rheological properties must be quantified. Physical characterization of by-products offers data needed for the design of equipment, processing facilities, and operations such as spray drying (Steffe, 1984). Little information has been gathered concerning the properties of livestock blood. Human blood, however, has been extensively studied, and provides a basis for reference.

The rheology of human blood is very complex. It depends on many factors, including shear rate, temperature, viscosity of plasma, viscosity of the red cells, internal viscosity of the red cells, red cell membrane properties, and red cell aggregation (Cokelet, 1972; Dintenfass, 1971). Andrews et al. (1992) asserts that blood viscosity varies between animal species, primarily due to differences in the shape and flexibility of the red blood cells.

Because pork production is very extensive in the U.S., and because there are numerous applications being developed for its by-products, the objective of this study was to characterize the rheological and physical properties

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of swine whole blood, blood plasma, and red blood cell samples which were collected at slaughter. Properties include apparent viscosity, density, surface tension, thermal conductivity, specific heat, and drying rate. These properties were studied at several temperatures.

MATERIALS AND METHODS

SAMPLE COLLECTION AND PREPARATION

Blood samples from typical slaughter hogs weighing between 91 to 113 kg (200 and 250 lb) were collected during swine slaughter from the Meat Laboratory of Iowa State University between the months of February and April 1996, and were immediately treated with sodium citrate anticoagulant at a concentration of 0.2 % (w/v), and mixed thoroughly. Each sample was taken from an individual hog and constituted approximately 2 L. The blood samples were then frozen and stored at -18°C until testing was initiated. Twenty blood samples were originally collected from swine slaughter; 10 samples were then randomly selected from the 20 for use in this study. After thawing for 24 h at 10°C , but before testing began, a portion of each blood sample was centrifuged at 10,000 G for 10 min to separate the blood into components (i.e., plasma and red cells). The separated red blood cells were a thick, semi-solid material, as shown later by the viscosity results. This procedure was similar to that described by Dintenfass (1971). Centrifugation was done after freezing and thawing (i.e., storage) in this study because this procedure is a common practice in the packing industry. However, because freezing was done prior to centrifuging, the plasma in this study was enriched with hemoglobin from ruptured red blood cells which resulted from the freezing process.

EXPERIMENTAL DESIGN

To investigate the effect of temperature on the physical properties of swine blood and its constituents, several temperature levels were used. Temperatures for the apparent viscosity, density, and surface tension tests were 5, 15, 25, and 35°C ; for the thermal conductivity tests, 5, 15, and 20°C ; for the specific heat tests, 15, 20, and 25°C ; and for the drying tests, 80, 100, and 120°C . Because the physical properties of biological materials often vary from sample to sample, a single-factor (e.g., temperature) randomized complete block experimental design was implemented (Neter et al., 1990; Stroshine and Hamann, 1995). Ten samples, or blocks, of each fluid (blood, plasma, and red cells) were tested at each temperature level for each physical property. For specific heat tests, only whole blood was studied. A sample size of ten was utilized to maintain both the Type-I and Type-II error rates at the 0.05 level for subsequent formal analyses. All collected data were then analyzed via a Statistical Analysis System software program (SAS, 1995).

APPARENT VISCOSITY

To measure the viscosity of the blood and component samples, a digital viscometer (Model LVTD, Brookfield Engineering, Stoughton, Mass.) with a concentric-cylinder spindle attachment (Model ULA, Brookfield Engineering, Stoughton, Mass.) was utilized. Apparent viscosity was determined at four shear rates: 1.83, 3.67, 7.34, and 14.68 s^{-1} . The testing procedure followed Test Method A of

ASTM Standard D 2196-86, which specifies standard testing methods for determining rheological properties of non-Newtonian materials (ASTM, 1991). To maintain a constant sample temperature during testing, the sample chamber was encased in a water jacket, through which water was pumped from a constant-temperature water bath.

DENSITY

The density of each fluid was determined by using specific gravity cups (Model H-38000-12, Cole-Parmer Co., Barrington, Ill.) and an electronic balance (Model DI-4KD, Denver Instrument Co., Arvada, Colo.). The specific gravity cups have a known mass and volume; hence, to measure density, a specific gravity cup was completely filled with the test fluid, excess fluid was removed, and the cup and fluid were then weighed on the balance.

SURFACE TENSION

A tensiometer was used to determine the surface tension of the fluids (Model 70545, CSC Scientific Co., Fairfax, Va.). The tensiometer was first calibrated with manufacturer standards. Then, a platinum-iridium ring was immersed in the test liquid, and the surface tension was subsequently determined by measuring the force required to withdraw the ring from the liquid's surface (CSC, 1989).

THERMAL CONDUCTIVITY

To determine thermal conductivity for each fluid sample, a line heat-source probe was constructed and implemented following the materials and procedures of Baghe-Khandan et al. (1981). Temperature rise over time was then monitored with a scanning thermocouple thermometer (DigiSense 92800-00, Cole-Parmer Co., Barrington, Ill.) in an 83-mL fluid sample. During each test, the electric current and voltage to the probe's heating wire, supplied by a power source (BK Model 1660A, Maxtec International, Chicago, Ill.), were monitored with multimeters (Fluke 77 and Fluke 88, John Fluke Co., Everett, Wash.). The thermal conductivity of each sample was then determined by the maximum slope method, as described by Wang and Hayakawa (1993).

SPECIFIC HEAT

The specific heat of the samples was determined by using the method of mixing, as described by Rizvi and Mittal (1992). The calorimeter was constructed from an insulated vacuum bottle (Stanley Model A-944DH, Aladdin Industries, Inc., Nashville, Tenn.), as described by Sweat (1986). A 400-g sample of cold blood ($5, 10, \text{ or } 15^{\circ}\text{C}$, $\pm 2^{\circ}\text{C}$) was then mixed with a 400-g sample of warm water ($25, 30, \text{ or } 35^{\circ}\text{C}$, $\pm 2^{\circ}\text{C}$): the cold sample was approximately 10°C below the final desired mixture temperature, while the warm sample was approximately 10°C above the final temperature. Before mixing, sample temperatures were measured with a thermometer (Barnart Model 115, Cole-Parmer Co., Barrington, Ill.). The mixture temperature was then monitored with a scanning thermocouple thermometer (DigiSense 92800-00, Cole-Parmer Co., Barrington, Ill.) until the mixture achieved thermal equilibrium.

DRYING ANALYSIS

To develop drying curves, 10-g fluid samples were placed in aluminum moisture dishes that were 8-cm in diameter and 2.5-cm in height (Style 10, Ellisco, Inc., Baltimore, Md.) which were then placed in a laboratory oven (Thelco Model 160DM, Precision Scientific, Inc., Chicago, Ill.) and sample mass over time was measured with an electronic balance (Model DI-4KD, Denver Instrument Co., Arvada, Colo.). The samples were dried at temperatures of 80, 100, and 120°C. Each drying test required 6 h, during which sample masses were recorded every 5 min for the first 90 min of testing and every 10 min thereafter. Thus, moisture content (d.b.) over time was monitored. Consequently, drying rates could be calculated for each moisture content, at each drying temperature.

RESULTS AND DISCUSSION

APPARENT VISCOSITY

For all fluids studied, both shear rate and temperature had a significant effect ($p < 0.05$) on apparent viscosity. Each fluid exhibited a decrease in apparent viscosity both as shear rate increased and as temperature increased. Thus, the results for each fluid followed rheological theory presented in the literature for pseudoplastic fluids (Steffe, 1984, 1992), which state that the relation between apparent viscosity and shear rate can be described by the following equation:

$$\eta_a = K \times \dot{\gamma}^{n-1} \quad (1)$$

where η_a is the apparent viscosity (Pa·s) at a given shear rate, $\dot{\gamma}$ is the applied shear rate (s^{-1}), K is a proportionality constant known as the consistency coefficient (Pa·sⁿ), and n is a power term, the flow behavior index. The values of K and n depend on the type of fluid under investigation. The relationship between shear stress and shear rate can then be described by the following power-law equation:

$$\tau = K \times \dot{\gamma}^n \quad (2)$$

where τ is the resulting shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), K is the consistency coefficient (Pa·sⁿ), and n is the flow behavior index (Steffe, 1984).

To subsequently relate shear stress to shear rate, and thus rheologically characterize the fluids, nonlinear regression methods were used to estimate consistency coefficient and flow behavior index values for each fluid at each temperature level (eq. 2). The results are shown in table 1. As the table shows, the consistency coefficient for each fluid decreased with increasing temperature. It appears, however, that the consistency coefficient for the red blood cells was more drastically influenced by temperature than those of the other fluids. Additionally, the flow behavior index decreased with temperature for the enriched plasma, but increased with temperature for whole blood and red blood cells.

As shown in this study, temperature has a substantial influence on rheological parameters. The effects of both shear rate and temperature on apparent viscosity can be combined into the following model:

Table 1. Consistency coefficients and flow behavior indices for swine blood and components

Fluid	Temp. (°C)	K (Pa·s ⁿ)	n (-)	R ²	C.V. (%)
Whole blood	5	0.26	0.30	0.95	7.79
	15	0.19	0.37	0.93	7.08
	25	0.16	0.39	0.94	7.22
	35	0.08	0.55	0.97	7.07
Plasma*	5	0.03	0.78	0.99	6.22
	15	0.03	0.80	0.86	7.92
	25	0.02	0.74	0.87	9.49
	35	0.02	0.68	0.96	8.88
Red cells	5	7.79	0.29	0.93	9.38
	15	5.03	0.38	0.89	9.13
	25	3.28	0.38	0.95	9.99
	35	1.75	0.46	0.89	9.10

* Plasma was enriched with ruptured red cell hemoglobin due to freezing prior to centrifugation.

$$\eta_a = K_T \times \exp\left(\frac{E_a}{RT}\right) \times (\dot{\gamma})^{\bar{n}-1} \quad (3)$$

where η_a is the apparent viscosity (Pa·s), K_T is a "combined" consistency coefficient (Pa·s ^{\bar{n}}), E_a is the activation energy for the fluid (J/gmol), R is the universal gas constant (8.315 J/gmol·K), T is the absolute temperature of the fluid (K), $\dot{\gamma}$ is the shear rate (s^{-1}), and \bar{n} is an "averaged" flow behavior index (Steffe, 1992). Consequently, the effects of both temperature and applied shear rate on the resulting shear stress can be combined into the following equation:

$$\tau = K_T \times \exp\left(\frac{E_a}{RT}\right) \times (\dot{\gamma})^{\bar{n}} \quad (4)$$

where τ is the shear stress (Pa) (Steffe, 1992). A generalized nonlinear regression procedure was implemented to determine a general prediction model to describe each fluid's rheological behavior over all temperature and shear rate ranges studied. With equation 3 as the model, the method of least squares was used in this nonlinear fitting procedure to determine estimates of the parameters K_T , (E_a/R), and ($\bar{n} - 1$) for the model equation. The resulting regression parameter estimates and the coefficients of determination and variation for each fluid are shown in table 2.

Human blood behaves as a pseudoplastic, or shear thinning, fluid due to the presence of the red blood cells suspended in the plasma which deform and orient in response to increasing shear rates (Dellimore and Campbell, 1978). Separated red blood cells also behave as a pseudoplastic fluid. Blood plasma, though, has been found to be Newtonian (Dintenfass, 1971). Thus, the results of this study for whole blood and red blood cells are

Table 2. Generalized nonlinear viscosity results for swine blood and components

Fluid	K_T (Pa·s ^{\bar{n}})	E_a/R (K)	$\bar{n} - 1$ (-)	R ²	C.V. (%)
Whole blood	0.01	2996.20	-0.76	0.92	7.17
Plasma*	1.41	866.29	-0.24	0.95	8.26
Red cells	0.01	4154.50	-0.73	0.85	9.42

* Plasma was enriched with ruptured red cell hemoglobin due to freezing prior to centrifugation.

consistent with behavior mentioned in the literature; however, the plasma in this study did not behave as a Newtonian fluid, as it should have according to Dintenfass (1971). This was probably due to the degradation and rupture of some of the red blood cells during the freezing and thawing process, and possibly due to a relatively high centrifugal force during separation, which then would have affected the resulting plasma composition, and hence, viscosity. Consequently, the “plasma” in this study presumably was a combination of plasma, ruptured red blood cells, and the interior, hemoglobin-rich fluid of the ruptured cells.

Also, relatively modest variation existed for the apparent viscosity data. This could have been due to natural variations between samples. Additionally, the variation might have been due to phenomena that occur when blood viscosity is tested in concentric-cylinder arrangements: red cell aggregation, migration, and sedimentation (Cokelet, 1972).

DENSITY

The results for the density experiments are shown in figure 1. The figure shows, for each fluid, the mean density value at each temperature level and the resulting linear regression curves ($\rho = aT + b$). For the fluids studied, density appeared to have a linear relationship with temperature; in fact, the average coefficient of determination for the regression curves was 0.97. It was found that temperature and fluid type each had a significant ($p < 0.05$) effect on the density measurements. The mean density of each fluid decreased with increasing temperature. Munson et al. (1990) stated that this behavior is typically exhibited by fluid materials. Furthermore, the resulting density for each liquid, at each temperature level, was slightly higher (1.0 to 6.3%) than the corresponding density for water. Additionally, little variability occurred in the data; the coefficient of variation ranged from 0.28 to 2.30% (not shown).

Cokelet (1972) reported that the density of human blood plasma is 1.05 g/mL; whereas, the density of human red blood cells is 1.09 g/mL. Dintenfass (1971) stated that the density of human plasma is 1.025 to 1.029 g/mL, the density of human red blood cells is 1.098 g/mL, and the density of whole human blood lies between 1.055 and 1.06 g/mL. No reference temperatures were found, however, for these literature values. Thus, the results from

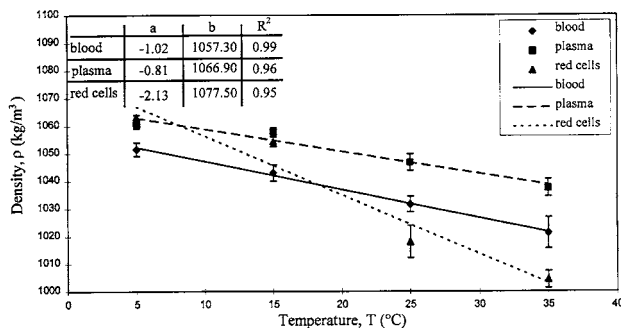


Figure 1—Mean density data (± 1 S.D.) and linear regression curves for swine blood and components (a is the linear regression slope and b is the y-intercept for $\rho = aT + b$).

this study were very similar to values described in the literature for human blood.

SURFACE TENSION

The results for the surface tension experiments are shown in figure 2. The figure shows the mean surface tension values at each temperature for each fluid. The figure also shows resulting linear regression curves ($\sigma = aT + b$). As with density, surface tension exhibited a slightly decreasing linear trend with temperature; the average coefficient of determination for the curves was 0.85. It was found that both temperature and fluid type had a significant effect ($p < 0.05$) on surface tension measurements. Additionally, the resulting surface tension for each liquid was lower than the corresponding surface tension for water (20.7 to 33.0%) at each temperature level. As with the density results, little variability occurred in the data. In fact, the coefficient of variation for the surface tension results ranged from 0.91 to 3.60% (not shown). Altman (1961) reported that the surface tension for human blood ranges from 55.5 to 61.2 dynes/cm; thus, the results for swine blood from this study are very similar to values for human blood. However, no reference temperatures were given in the literature consulted.

THERMAL CONDUCTIVITY

The results of the thermal conductivity experiments are shown in table 3. Both temperature and fluid type had a significant effect ($p < 0.05$) on thermal conductivity measurements. The thermal conductivity results, however, did not clearly indicate a pattern with temperature: thermal conductivity of the plasma increased with temperature from 5 to 20°C; whereas, the thermal conductivity of the whole blood and red cells increased from 5 to 15°C but decreased from 15 to 20°C. The coefficient of variation for the thermal conductivity results ranged from 2.36 to 9.93%. No data for the thermal conductivity of other bloods was found in the literature. The thermal conductivity of other fluids, such as glycerin and water, however, decreases with increasing temperature (Incropera and DeWitt, 1990). Furthermore, the thermal conductivity results for each liquid, at each temperature level, were lower than the corresponding thermal conductivity values for water by 42.0 to 57.0%.

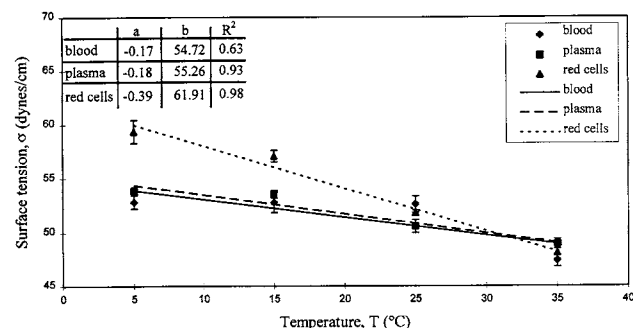


Figure 2—Mean surface tension data (± 1 S.D.) and linear regression curves for swine blood and components (a is the linear regression slope and b is the y-intercept for $\sigma = aT + b$).

Table 3. Thermal analysis results for swine blood and components*

Thermal Cond. (W/mK)	Temperature (°C)					
	5		15		20	
	Mean	C.V. (%)	Mean	C.V. (%)	Mean	C.V. (%)
Whole blood	0.2478 ^a	6.04	0.3004 ^b	8.88	0.2798 ^b	5.51
Plasma †	0.2716 ^b	8.21	0.3330 ^c	7.95	0.3504 ^c	9.93
Red cells	0.3038 ^b	8.16	0.3293 ^c	9.72	0.3093 ^b	2.36

Thermal Cond. (W/mK)	Temperature (°C)					
	15		20		25	
	Mean	C.V. (%)	Mean	C.V. (%)	Mean	C.V. (%)
Whole blood	3.7966 ^a	9.75	3.5084 ^b	2.61	3.4543 ^b	4.90

* Nonsimilar letters for a given property indicate a significant difference at the 0.05 level.

† Plasma was enriched with ruptured red cell hemoglobin due to freezing prior to centrifugation.

SPECIFIC HEAT

The specific heat results for whole blood are also shown in table 3. Due to a limited supply of plasma and red cell samples, specific heat tests were conducted only on whole blood. Temperature had a significant ($p < 0.05$) effect on specific heat. In fact, specific heat decreased as temperature increased. No data were available in the literature for the specific heat of whole blood. But, the specific heat results for swine blood were 9.0 to 17.4% lower than the respective values for water at each temperature. Additionally, the coefficient of variation ranged from 2.61 to 9.75% for the specific heat measurements; therefore, the variability in the data was relatively low.

THERMAL DIFFUSIVITY

Data on thermal conductivity, density, and specific heat were all gathered for whole swine blood only; thus, the thermal diffusivity for whole blood could be determined as $\alpha = k / (\rho \times c_p)$, where α is the calculated thermal diffusivity (m^2/s), k is the thermal conductivity (W/m·K), ρ is the density (kg/m^3), and c_p is the specific heat (J/kg·K). At temperatures of 15, 20, and 25°C, the calculated thermal diffusivity for whole swine blood was 7.09, 8.06, and $8.59 \times 10^{-8} m^2/s$, respectively.

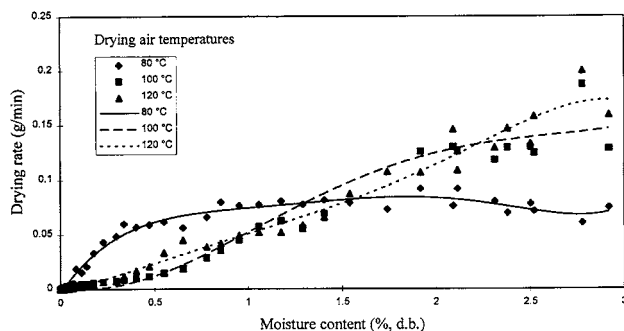


Figure 3–Drying data and regression curves for whole swine blood.

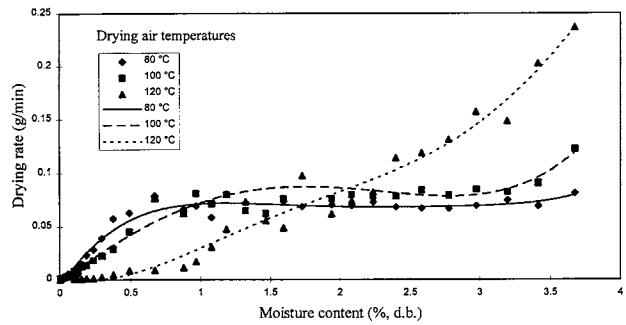


Figure 4–Drying data and regression curves for enriched swine plasma.

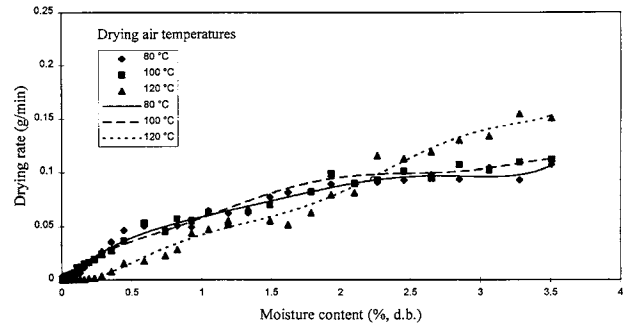


Figure 5–Drying data and regression curves for swine red blood cells.

DRYING ANALYSIS

In the drying analysis, four samples of each fluid were utilized at each drying temperature. Figures 3 through 5 show the drying data and resulting model fits of the drying processes for whole blood, blood plasma, and red blood cells, at drying temperatures of 80, 100, and 120°C. These curve fits are fifth-order polynomial regression lines with an average coefficient of determination of 0.96.

For whole blood (fig. 3) falling rate periods appear to begin at moisture contents (d.b.) of 0.6 and 0.25 at a drying temperature of 80°C; at approximately 2.25 and 1.4 at 100°C; and at 2.8 and 1.6 at 120°C. For plasma (fig. 4) falling rates seem to begin at moisture contents (d.b.) of approximately 0.8 and 0.4 at a drying temperature of 80°C; at 1.4 and 1.0 at 100°C; and at 2.9, and some value greater than 3.7, at 120°C. Red blood cells (fig. 5) exhibit falling rates which appear to begin at moisture contents (d.b.) of 2.5, 0.7, and 0.25 at a drying temperature of 80°C; at 3.5, 2.15, and 0.3 at 100°C; and at approximately 3.1, 1.75, 0.9, and at some value greater than 3.5, at 120°C.

Each graph seems to indicate that as drying temperature increases, the moisture contents at which the falling rates begin also increase, regardless of which fluid is under analysis. Furthermore, the drying curves for the red blood cells seem to differ substantially from the curves for the whole blood and plasma, which appear very similar to each other.

In this study, no proximate analysis was directly conducted on swine blood or its constituents; several previous authors, though, have published results for these studies. Wang et al. (1996) collected swine blood from the same source as the authors of this article, and studied dried whole blood and red blood cells, and found protein concentrations of 93.6 and 98.3% (d.b.), respectively; ash

of 5.2 and 4.2%, respectively; and 0.3% lipids for the red blood cells. Howell and Lawrie (1983) studied liquid swine blood plasma and found a protein concentration of 6.8%, an ash concentration of 1.1%, and a lipid concentration of 0.15%. Donnelly et al. (1978) also examined swine blood plasma and found 6.1% protein, 0.2% nonprotein nitrogen, 1.7% ash, 0.2% fat, 8.5% total solids, and a mean pH of 7.8. Proximate analysis is important because it quantifies the components of a sample. Thus, a future study that would correlate proximate analyses of swine blood, plasma, and red blood cells to the physical and rheological properties would provide valuable information concerning the properties of these materials. Also, a study on the effect of storage time and frozen temperature should be considered to determine their effect on the red cells rupture.

SUMMARY AND CONCLUSIONS

Anticoagulated swine blood, hemoglobin-enriched blood plasma, and red blood cells all exhibited pseudoplastic behavior when subjected to concentric-cylinder viscometer testing. Shear rate affected the apparent viscosity of the fluids, as did temperature: increasing shear rate and increasing temperature both produced a decrease in apparent viscosity for all fluids. Red blood cells manifested the highest viscosity overall; whereas, the whole blood was somewhat less viscous. Enriched blood plasma was the least viscous of all the fluids, and although studies on human plasma characterize it as Newtonian, the enriched blood plasma also exhibited a pseudoplastic behavior. This was probably due to red cell rupture during freezing and thawing before experimentation, and possibly due to a high centrifugal force during separation which also could have caused red cell rupture.

The whole blood, enriched blood plasma, and red blood cells all exhibited a decrease in density with an increase in temperature. At each temperature level, all fluids produced density readings 1.0 to 6.3% higher than the respective values for water. Also, the whole blood, enriched blood plasma, and red blood cells all displayed a decrease in surface tension with an increase in temperature. At each temperature level, all fluids produced surface tension values 20.7 to 33.0% lower than the respective values for water.

Although temperature was found to be significant, the actual temperature dependence of the thermal conductivity values for the fluids studied was unclear. It was determined, however, that the thermal conductivity values for whole blood, enriched plasma, and red blood cells were 42.0 to 57.0% lower than the respective values for water at each temperature. Furthermore, it was determined that temperature had a significant effect on the specific heat values for whole blood. In fact, the specific heat was found to decrease with increasing temperature. The experimental values of specific heat were found to be 9.0 to 17.4% lower than those of water at each temperature. Moreover, from the drying curves which were determined, for all fluids studied, as drying temperature increased, the moisture contents at which the falling rates began also increased.

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