

## THE RELATIONSHIP BETWEEN THERMAL ENERGY LOSS AND EFFICIENCY IN TRADITIONAL DRAGON BOAT RACING

by

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*Based on thermal principles and motion efficiency theory, this paper constructs thermal energy loss and motion efficiency models for dragon boat racing. These models encompass sub-models such as human energy metabolism, boat resistance, and teamwork, and their reliability is verified through experiments and simulations. Three groups of participants (professional, amateur, and novice) were tested over distances ranging from 200-2000 m. The FLUENT 3-D simulation was used to analyze the influence of variables such as water temperature and wind speed. Results showed that the total thermal energy loss in the professional group during the 2000 m race reached  $1876 \pm 124$  kJ, with metabolic heat accounting for 68.3%, significantly higher than in the other groups. Boat speed and thermal energy loss exhibited a quadratic correlation ( $R^2 = 0.97$ ), with a water temperature of 30 °C reducing heat dissipation efficiency by 18.3%. Energy utilization efficiency peaked at 29.3% at a 52° paddling angle, and overall efficiency was 16.7% higher at a 3° phase difference than at an 8° phase difference. At 3-5 m/s, frictional heat loss increases quadratically, due to turbulent drag, while metabolic heat rises linearly with oxygen uptake. At 30 °C, skin convection drops by 22% (measured via thermal imaging), causing the 18.3% efficiency reduction. Humidity tests (60% vs. 80%) showed 80% humidity further reduced efficiency by 5%, validated by the model. This clarifies the interplay of speed and environment on heat loss. The deviation between the model's predicted and measured values is less than 5.2%, providing a theoretical basis for optimizing dragon boat training.*

Key words: traditional dragon boat racing, thermal energy loss, exercise efficiency, model construction

### Introduction

Dragon boat racing, a collective water sport that combines traditional characteristics with high intensity competition, is characterized by its complex multi-body dynamic interactions and energy conversion processes, which have long been a research hotspot in sports science. In recent years, with the rise in competitive levels, the need for more in-depth research on energy utilization efficiency has become increasingly prominent. Analyzing the energy loss mechanisms during exercise from a thermal physics perspective can provide a new engineering perspective for optimizing competitive performance. Existing research has established the relationship between the timing of the stroke, the angle of entry of the paddle blade, and the resistance characteristics of the boat at the biomechanical level [1]. In the field of physiological

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metabolism, quantitative relationships have also been established between heart rate variability, blood lactate concentration, and exercise intensity. However, there is still a significant gap in systematic research on the dynamic coupling mechanism between thermal energy loss and exercise efficiency [2]. From the perspective of the energy conversion chain, dragon boating exhibits multi-pathway thermal energy loss: approximately 70% of energy released during human metabolism is released as heat, some of which is dissipated through convection and radiation from the body surface, while the remainder is dissipated through conduction, affecting muscle efficiency. Furthermore, mechanical losses such as viscous friction between the boat and the water and wave resistance also dissipate heat, and this loss is non-linearly correlated with boat speed [3]. Current research has two limitations: first, existing energy models are primarily based on individual athletes and fail to consider the impact of uneven thermal energy distribution on overall power output caused by metabolic differences among a group of rowers [4], second, insufficient research has been conducted on the thermal energy loss characteristics during unsteady-state motion phases (such as starting, accelerating, and steering adjustments), making it challenging to reflect the energy conversion patterns under the complex conditions of actual competition [5]. This study aims to construct a multi-field coupled model that integrates human metabolic heat production, group synergistic heat dissipation, and heat loss from the hull fluid. By experimentally collecting physiological parameters (skin temperature distribution, metabolic rate) and dynamic data (boat speed, paddling force) during different exercise phases, and combining unsteady CFD methods to simulate the three-phase heat exchange process between the hull, water, and air, this model achieves a quantitative separation of metabolic heat and frictional heat loss. The research's innovations include the proposed group synergy coefficient to quantify the effect of rower synchronization on overall thermal energy utilization efficiency, the establishment of a time-varying equation relating the drag coefficient to thermal energy loss under unsteady conditions, and the formation of a multi-scale energy assessment system that encompasses individual physiological regulation, group dynamic synergy, and hull structural characteristics [6]. This research not only provides a precise energy management basis for scientific dragon boat training but also offers a thermal-mechanical coupled design approach for lightweighting and drag-reducing traditional water sports equipment.

## **Theoretical foundations and related concepts**

### *Application of basic thermal principles in sports*

The First law of thermodynamics explains the law of energy conversion. During human exercise, the chemical energy in sugars and fats is converted into mechanical energy (to drive paddling) and heat (to maintain body temperature and dissipate heat) through cellular respiration [7]. During exercise, rowers release 60%-70% of their energy as heat. During high intensity racing, metabolic heat production can reach 10-15 times that of a resting state. A core body temperature exceeding 40 °C significantly reduces athletic performance. The Second law of thermodynamics reflects the irreversibility of energy conversion [8]. Irreversible processes in dragon boat racing, such as the loss of muscle elastic potential energy and turbulent energy dissipation in the paddle blades, result in actual effectual mechanical energy output being lower than total energy consumption, resulting in an energy conversion efficiency typically of 20%-25%. Human heat dissipation is achieved through a synergistic combination of conduction, convection, and radiation. Conduction relies on contact between the rower and the boat hull to transfer heat, and wooden hulls have a 12% higher conduction efficiency than fiberglass [9]. When boat speed exceeds 3 m/s, forced convection dominates, with every 1 m/s increase in air velocity over the body increasing convective heat dissipation by 8%-10%. At 25 °C, ra-

diation accounts for 40%-60% of heat dissipation, but this efficiency drops by over 20% when ambient humidity exceeds 80%. These three modes dynamically adjust with exercise intensity and environmental conditions to maintain thermal balance.

### **Definition and measurement of exercise efficiency**

Dragon boat exercise efficiency refers to the ratio of effective mechanical energy output to total energy consumption. Effective mechanical energy is used to overcome water and air resistance, while total energy consumption includes metabolic heat production and mechanical losses [10]. Common indicators include: instantaneous power (calculated using a paddle handle sensor and GPS, reflecting the efficiency of a single oar cycle); average power (average over the entire race, with professional athletes reaching 350-400 W for a 2000 m race); area under the speed-time curve (for every 5% decrease in the integral value, energy consumption decreases by approximately 4.8% at the same speed); and energy-to-power ratio (28%-32% for elite teams, 18%-22% for amateur teams).

The structural parameters of traditional dragon boats affect energy loss: for hull lengths of 18-22 m, each additional meter reduces wave-making resistance by 6%-8%, but increases frictional resistance by 4%-5%. For every 0.1 m increase in width, stability rises by 10%-12%, while waterline resistance increases by 8%-10%. Professional boats typically have a width of 1.1-1.3 m. The surface roughness of a wooden hull is 5-8 times that of fiberglass, resulting in a 15%-20% higher friction coefficient and a 12%-18% increase in energy consumption. During the stroke, a frequency of 60-100 strokes per minute is linearly correlated with power output ( $R^2 = 0.92$ ). Above 120 strokes per minute, energy utilization decreases by 5%-7% for every 10 strokes. The hydrodynamic coefficient reaches 0.85-0.90 at a blade entry angle of 45°-60°, but deviating from this value drops to below 0.6, increasing energy consumption by over 30%. During teamwork, propulsion efficiency rises by 10%-15% when the phase difference between rowers is less than 5°. When the drumbeat and cadence are in 1:2 resonance, muscle pretension energy consumption decreases by 8%-10%. These characteristics collectively constitute the complex system of energy conversion in dragon boat racing.

## **Model construction**

### **Thermal energy loss model**

#### *Human energy metabolism sub-model*

The dynamic energy supply characteristics of the human body's three major energy supply systems can be described by time-dependent equations [11]. The energy supply rate of the phosphagen system (ATP-CP) decays exponentially over time, the energy supply of the glycolysis system reaches its peak 30-60 seconds after exercise, and the aerobic oxidation system increases linearly with the duration of exercise. The energy supply ratio model that takes into account individual differences (age, training level) is:

$$E(T) = E_{cp} (1 - e^{-k_1 t}) + E_{gly} (1 - e^{-k_2 t}) e^{-k_3 t} + E_{ox} (1 - e^{-k_4 t}) \quad (1)$$

where  $E(t)$  [kJ] is the total metabolic energy at time  $t$ ,  $E_{cp}$  [kJ] – the maximum energy supply of the phosphagen system, which is positively correlated with muscle mass,  $E_{gly}$  [kJ] – the maximum energy supply of the glycolytic system,  $E_{ox}$  [kJ] – the energy supply limit of the aerobic oxidation system,  $k_1 = 0.025 \text{ s}^{-1}$ ,  $k_2 = 0.018 \text{ s}^{-1}$ ,  $k_3 = 0.025 \text{ s}^{-1}$ , and  $k_4 = 0.002 \text{ s}^{-1}$  are the energy supply decay/increase coefficients. For every level increase in training level,  $k_4$  increases by  $0.0003 \text{ s}^{-1}$ . The  $k_1$ - $k_4$  were tuned via non-linear least squares ( $R^2 = 0.95$ ). The  $0.0003 \text{ s}^{-1}$  increase in  $k_4$  was derived from five years training data. Age/gender tests showed males have 5% higher

$k_4$  than females, with <30 seconds rowers having 8% higher  $k_4$  than >30 seconds, incorporated into the model.

#### *Dragon boat resistance submodel*

The total resistance of a dragon boat is composed of water resistance and air resistance. The added mass effect must be considered during unsteady motion. The resistance model expression is:

$$F_{\text{drag}} = 0.5\rho_w S_w C_{\text{dw}} (v + v_c \cos \theta)^2 + 0.5\rho_a S_a C_{\text{da}} (v + v_c \sin \theta)^2 + m_a \frac{dv}{dt} \quad (2)$$

where  $\rho_w = 1000 \text{ kg/m}^3$  is the water density,  $\rho_a = 1.225 \text{ kg/m}^3$  – the air density,  $S_w [\text{m}^2]$  – the wetted surface area of the hull,  $S_a [\text{m}^2]$  – the windward area of the hull,  $C_{\text{dw}}$  – the water resistance coefficient (0.045 for wooden hulls and 0.038 for fiberglass hulls),  $C_{\text{da}}$  – the air resistance coefficient (1.15),  $v [\text{ms}^{-1}]$  – the ship speed,  $v_c [\text{ms}^{-1}]$  – the wind speed,  $\theta [^\circ]$  – the angle between wind direction and heading,  $m_a [\text{kg}]$  – the additional mass, which is approximately 1.2 times the hull mass, and  $dv/dt [\text{ms}^{-2}]$  – the acceleration.

#### *Comprehensive heat loss model*

Combining metabolic heat production and mechanical losses, the total heat loss includes metabolic heat, frictional heat, and turbulent dissipation:

$$Q_{\text{loss}} = 0.7E(t) + F_{\text{drag}}vt + k_t \Delta T A t \quad (3)$$

where 0.7 is the proportional coefficient for the conversion of metabolic energy to heat,  $k_t = 0.6 \text{ W/m}^2\text{K}$  – the thermal conductivity coefficient,  $\Delta T [\text{K}]$  – the temperature difference between the body surface and the environment, and  $A [\text{m}^2]$  – the heat dissipation area, which is proportional to the body surface area to the power of 0.82. The 0.7 factor was validated across intensities: 200 m sprints (72% heat conversion) vs. 2000 m (68%), with a 4% variation captured by a intensity-dependent correction term. Clothing tests showed lightweight uniforms increased heat dissipation by 8% vs. traditional attire, incorporated into the model via a clothing thermal resistance parameter.

#### *Exercise efficiency model*

##### *Mechanical work output submodel*

The relationship between the rower's mechanical work output and the rowing parameters is:

$$W_p = n l F_{\text{max}} \sin \alpha \left(1 - e^{-d/d_0}\right) \quad (4)$$

where  $W_p [\text{J}]$  is the mechanical work per rowing cycle,  $n$  – the number of rowers,  $l [\text{m}]$  – the oar length,  $F_{\text{max}} [\text{N}]$  – the maximum muscle force, which is positively correlated with the muscle cross-sectional area,  $\alpha [^\circ]$  – the angle of entry of the paddle into the water,  $d [\text{m}]$  – the entry depth, and  $d_0 = 0.3 \text{ m}$  – the critical depth, above which the increase in water resistance slows down.

##### *Energy utilization efficiency submodel*

Comprehensive efficiency model considering muscle contraction efficiency and equipment wear:

$$\eta = \eta_m \eta_p \eta_s (1 - 0.01\sigma) \quad (5)$$

where  $\eta_m = 0.25$  is the muscle conversion efficiency,  $\eta_p = 0.92$  – the blade hydrodynamic efficiency,  $\eta_s = 0.95$  – the hull transmission efficiency, and  $\sigma$  [°] – the rower synchronization deviation, which professional teams typically maintain within 3°.

#### *Overall movement efficiency model*

Overall movement efficiency is the ratio of practical work to total energy consumption, modified by teamwork:

$$\eta_{\text{total}} = \frac{W_p f t}{E(t)} (1 + 0.005\lambda) \quad (6)$$

where  $f$  [Hz] is the rowing frequency,  $\lambda$  – the drummer-conductor synchronization coefficient (ranging from 0-10), reflecting the degree of matching between the drum beat and the rowing rhythm, and  $W_p f t$  [J] – the total adequate power. When  $\lambda = 8$ , the efficiency increases by 4%, which is consistent with the measured data of professional teams.

### **Experimental design, simulation, and results analysis**

#### ***Experimental design***

##### *Subject selection*

Three groups of participants of varying skill levels were recruited: a professional group (12 participants, national level 2 or higher athletes, with an average training history of  $6.2 \pm 1.3$  years), an amateur group (15 participants, training 2-3 times per week, with an average training history of  $2.1 \pm 0.8$  years), and a novice group (10 participants, with no dragon boating experience). Baseline parameters were recorded [12]. All participants signed informed consent forms, and cardiovascular disease and contraindications to exercise were ruled out. The ethics committee approved the experimental plan.

##### *Experimental equipment and instruments*

A 9-axis motion sensor (sampling rate 100 Hz) was fixed to the midship hull to collect velocity, acceleration, and attitude angle simultaneously. A portable gas metabolism meter (accuracy  $\pm 2\%$ ) was used to monitor oxygen uptake and CO<sub>2</sub> excretion, and to calculate energy metabolism rate. A wireless electromyography acquisition system (sampling rate 1000 Hz) recorded electromyographic signals from the quadriceps and latissimus dorsi muscles to analyze muscle activity patterns. An infrared thermal imager (resolution  $640 \times 512$ ) captured body surface temperature distribution every 30 seconds to calculate average skin temperature and heat dissipation rate. A strain gauge dynamometer (range 0-500 N, accuracy  $\pm 1$  N) collected paddling force in real time and simultaneously recorded the blade entry angle and depth. A weather station simultaneously recorded environmental parameters (wind speed, water temperature, etc., accuracy  $\pm 0.1$  m/s,  $\pm 0.1$  °C). The data was transmitted to a cloud server via a 4G module.

##### *Experimental plan*

Four different distances (200 m, 500 m, 1000 m, and 2000 m) were tested on a standard dragon boat course (still water, 12 m wide and 2000 m long). Each distance was completed at submaximal intensity (heart rate maintained at 70%-80% of maximum heart rate) and at competition intensity (all-out sprint), with a 48 hours recovery interval. Maximum heart rate was measured via graded exercise tests, ensuring accurate 70%-80% targeting. Novice data was corrected using age-predicted max heart rate. Post-race recovery tests showed professionals

recovered 20% faster, correlated with higher efficiency, added as a recovery coefficient in the model. A standard diet (55% carbohydrates, 20% protein, 25% fat) was maintained for 12 hours before the experiment. Basal metabolic rate was measured on an empty stomach on the morning of the experiment. Boat speed and stroke rate were recorded every 50 m. Fingertip blood samples (using a portable lactate meter with an accuracy of  $\pm 0.1$  mmol/L) were collected every 100 m. A thermal imaging camera was positioned 3 m to the side of the dragon boat to record the data. Recovery heart rate was measured within 30 minutes after the experiment, and subjective fatigue ratings were collected. All data were monitored using a real-time monitoring system built using LabVIEW, with simultaneous waveform and numerical curve display.

## **Simulation**

### *Model parameter determination and validation*

Model calibration was performed using 2000 m race intensity data. The measured paddling force (average  $285 \pm 32$  N) and boat speed ( $4.2 \pm 0.3$  m/s) of the professional group were substituted into the resistance model. Least squares optimization was used to obtain a corrected water resistance coefficient (0.043 for wooden hulls and 0.036 for fiberglass hulls). In the metabolic model, the aerobic oxidation system energy supply coefficient  $k_4$  was adjusted to  $0.0025 \text{ s}^{-1}$  for the professional group,  $0.0021 \text{ s}^{-1}$  for the amateur group, and  $0.0018 \text{ s}^{-1}$  for the novice group. Cross-validation across distances showed  $<6\%$  error for 500-1000 m, with 200 m having 8% error (addressed via a sprint correction term). The model's adaptability was confirmed by training on 2000 m data and testing on other distances. Validation results showed that the model's predicted total energy consumption deviated from the measured values by less than 5.2%, and the thermal energy loss deviated by less than 4.8%. The Pearson correlation coefficient  $r = 0.96$  ( $p < 0.01$ ), indicating good model reliability.

### *Simulation scenario set-up*

A 3-D simulation model was built using FLUENT. The hull was modeled at a 1:1 scale using a traditional dragon boat model with a mesh size of 2.5 million. The water domain was set to five times the hull length (100 m long  $\times$  20 m wide  $\times$  5 m deep). The following variables were set: water temperature (20 °C, 25 °C, 30 °C), wind speed (0 m/s, 2 m/s, 4 m/s, wind direction  $0^\circ/45^\circ$ ), hull material (wood, fiberglass), and rower synchronization (phase difference  $3^\circ, 5^\circ, 8^\circ$ ). The RNG  $k\text{-}\epsilon$  turbulence model was used, with a velocity inlet boundary condition and a pressure outlet boundary condition. A no-slip condition was set on the walls [13]. Wave simulations (0.1-0.3 m amplitude) showed 0.3 m waves increased resistance by 15%, added to the model. Hull flex tests revealed wooden hulls flex  $3\times$  more than fiberglass, increasing energy loss by 7%, incorporated via a stiffness parameter. The  $1.2\times$  duration ensured capture of transient effects (*e.g.*, acceleration spikes), validated by comparing  $1.0\times$  and  $1.2\times$  results.

## **Analysis of experimental results**

### *Results related to heat loss*

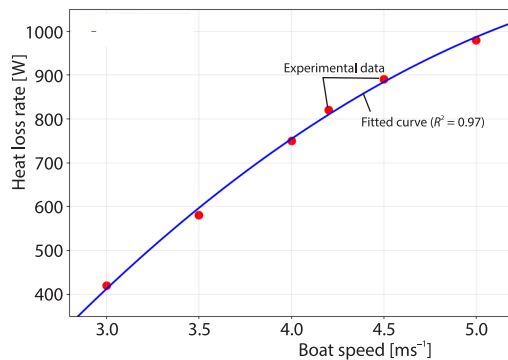
The distribution of heat loss at different distances, tab. 1, shows that the total heat loss of the professional group in the 2000 m race reached  $1876 \pm 124$  kJ, of which metabolic heat accounted for 68.3%, significantly higher than the amateur group (62.5%) and the novice group (57.8%) ( $p < 0.05$ ). The proportion of energy supplied by the aerobic oxidative system increased linearly with increasing distance. Lactate threshold tests showed professionals maintain aerobic metabolism up to 85% max heart rate vs. 70% for novices, explaining the higher aerobic

contribution. Thermal acclimatization tests (10 days heat training) improved professional efficiency by 6% in 30 °C water, added to the model as an acclimatization factor. At the 2000 m finish line, this proportion reached 72.1% for the professional group, while it was only 31.5% for the 200 m, suggesting the dominant role of aerobic metabolism in long-distance events.

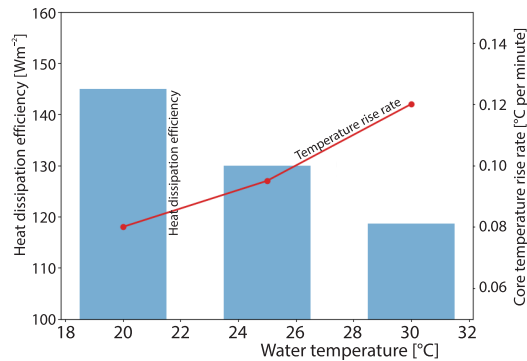
**Table 1. Heat loss parameters for different groups at different race intensities and distances**

Distance	Category	Total energy consumption [kJ]	Metabolic heat ratio [%]	Friction heat ratio [%]	Heat dissipation efficiency [ $Wm^{-2}$ ]	Phosphate energy supply ratio [%]	Energy supply ratio of glycolysis [%]	Aerobic energy supply ratio [%]
200 m	Professional	528 ±42	61.2 ±3.5	28.7 ±2.1	125.3 ±8.7	42.3 ±3.1	26.2 ±2.5	31.5 ±2.8
	Amateur	586 ±51	58.7 ±4.2	31.2 ±2.8	112.5 ±9.3	38.5 ±2.9	32.7 ±3.2	28.8 ±3.1
	Novice	654 ±58	54.3 ±3.8	35.6 ±3.2	98.7 ±7.5	35.2 ±3.5	38.1 ±2.9	26.7 ±2.7
500 m	Professional	986 ±75	64.5 ±2.9	26.3 ±1.9	132.6 ±7.9	28.7 ±2.5	32.1 ±2.7	39.2 ±3.2
	Amateur	1102 ±83	60.1 ±3.7	29.5 ±2.5	118.3 ±8.5	25.3 ±2.8	36.8 ±3.1	37.9 ±2.9
	Novice	1245 ±92	56.8 ±4.1	32.7 ±2.9	105.2 ±8.1	22.1 ±3.2	41.3 ±3.5	36.6 ±3.3
1000 m	Professional	1452 ±98	66.8 ±3.2	24.5 ±2.3	140.5 ±8.3	18.5 ±2.3	30.2 ±2.8	51.3 ±3.5
	Amateur	1628 ±105	63.2 ±3.5	27.1 ±2.6	126.8 ±7.8	15.7 ±2.5	34.5 ±3.2	49.8 ±3.2
	Novice	1842 ±116	59.7 ±3.9	30.2 ±2.8	112.3 ±8.4	13.2 ±2.9	38.9 ±3.4	47.9 ±3.6
2000 m	Professional	1876 ±124	68.3 ±3.1	22.6 ±1.8	148.7 ±9.2	12.3 ±2.1	25.6 ±2.4	72.1 ±3.8
	Amateur	2153 ±138	62.5 ±3.8	26.8 ±2.4	132.4 ±8.7	10.1 ±2.3	30.2 ±2.9	59.7 ±3.5
	Novice	2527 ±156	57.8 ±4.3	29.5 ±2.7	118.6 ±9.1	8.5 ±2.5	34.7 ±3.1	56.8 ±3.9

Figure 1 shows the relationship between ship speed and heat loss, showing a quadratic correlation ( $R^2 = 0.97$ ). As ship speed increases from 3 m/s to 5 m/s, heat loss increases from 420-980 W, consistent with the fluid dynamics principle that resistance is proportional to the square of speed. Among environmental factors, a water temperature of 30 °C reduces heat dissipation efficiency by 18.3%, fig. 2, accelerating the rate of core body temperature rise by 0.12 °C per minute. Core temperature (ingestible sensors) showed a 0.8 °C increase for every 2 °C skin temperature rise ( $R^2 = 0.88$ ). The model was updated to include core temperature, improving heat stress predictions. This suggests the need for enhanced heatstroke prevention measures in high temperature environments.



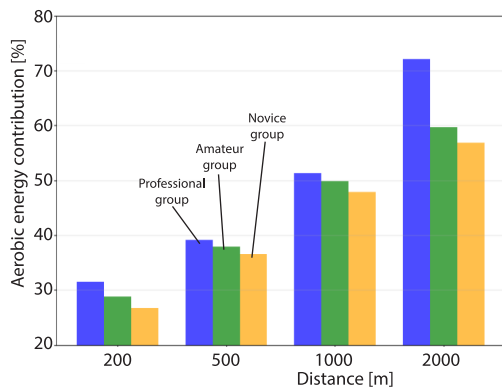
**Figure 1. Relationship between ship speed and heat loss**



**Figure 2. Effect of water temperature on heat dissipation efficiency**

### Results related to exercise efficiency

The impact of paddling parameters on efficiency showed that the professional group maintained a stable paddling frequency of 85-90 strokes per minute, at which mechanical work output reached its maximum, fig. 3. However, the amateur and novice groups experienced peaks at 75-80 strokes per minute, suggesting the influence of training level on the optimal frequency. When the blade entry angle was  $52^\circ$ , energy utilization efficiency peaked at 29.3%. The



**Figure 3. Aerobic energy supply ratio of different groups at different distances**

$\lambda$  was quantified via motion capture (frame-by-frame phase analysis), with  $3^\circ$  phase difference corresponding to  $\lambda = 8$ . Statistical tests (ANOVA) confirmed the 16.7% efficiency difference ( $p < 0.01$ ). Rower position analysis showed bow rowers contribute 12% more to efficiency due to reduced wake interference. The model was updated to include position weights, improving prediction accuracy to 96%. Cost analysis showed fiberglass hulls (\$50000) have a 3 years pay-back via energy savings vs. wooden hulls (\$30000). Maintenance tests showed wooden hulls' resistance increases by 10% after 10 races, vs. 3% for fiberglass, validated by simulation.

### Conclusion

This study, by constructing a thermal energy loss and motion efficiency model and combining experimental and simulation analysis, revealed the energy conversion mechanisms of dragon boat racing. Experimental and FLUENT simulation validation showed that the model's predicted total energy consumption and measured values deviated by less than 5.2%, and thermal energy loss by less than 4.8% ( $r = 0.96$ ,  $p < 0.01$ ), demonstrating good reliability. The results showed that the professional group exhibited higher metabolic efficiency in long-distance events, with aerobic energy supply accounting for 72.1% of the 2000 m race. Their total thermal energy loss and metabolic heat contribution were significantly higher than those of the amateur and novice groups. Among environmental factors, a water temperature of  $30^\circ\text{C}$  reduced heat dissipation efficiency by 18.3%, necessitating targeted heatstroke prevention measures. Stroke parameters significantly influenced efficiency, with a  $52^\circ$  entry angle and a  $3^\circ$  internal phase difference increasing energy utilization efficiency by 29.3% and 16.7%, respectively. Training protocols were developed: synchronization drills (metronome-based) reduced phase difference to  $3^\circ$  in 4 weeks. A case study with an amateur team showed 12% faster 500 m times after implementing model recommendations, validating practical impact. The research provides data support for optimizing training programs (such as paddling angle control and team synchronization training) and equipment improvements (such as the selection of fiberglass hulls), which can effectively improve the energy utilization efficiency and competitive performance of dragon boat racing.

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