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Evaporative Air Coolers Optimization for Energy Consumption Reduction and Energy Efficiency Ratio Increment

Leila Torkaman, Nasser Ghassembaglou

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Abstract—Significant quota of Municipal Electrical Energy consumption is related to Decentralized Air Conditioning which is mostly provided by evaporative coolers. So the aim is to optimize design of air conditioners to increase their efficiencies. To achieve this goal, results of practical standardized tests for 40 evaporative coolers in different types collected and simultaneously results for same coolers based on one of EER (Energy Efficiency Ratio) modeling styles are figured out. By comparing experimental results of different coolers standardized tests with modeling results, preciseness of used model is assessed and after comparing gained preciseness with international standards based on EER for cooling capacity, aeration, and also electrical energy consumption, energy label from A (most effective) to G (less effective) is classified; finally needed methods to optimize energy consumption and coolers' classification are provided.

Keywords—Cooler, EER, Energy Label, Optimization.

I. INTRODUCTION

BECAUSE of evaporative coolers dependency on evaporation, they are vastly used in arid areas [1]. Referring to psychometric chart shows an overlapping on adiabatic saturation line by evaporative cooling process; tendency of output air relative humidity to 100% draws humid air temperature to wet bulb which is the least possible amount; however, to obtain this, thickness of straw should be increased which increases pressure drop and finally flow rate; therefore, it is needed to optimize operational effective variables.

Therefore, standard tests have been done on 40 samples which encompass comparison and probation on followings:

1. Measurement of output dry bulb temperature
2. Foaming measurement
3. Measurement of Consumed electrical power
4. Estimating sensible cooling capacity
5. Energy Efficiency Ratio calculation
6. Numerical comparison of experimental and modeling results
7. Classification of energy label

II. MEASUREMENTS

In the sake of dynamic pressure measurement at end of channel a diagonal differential monometer has been used [2]. The amount of flowing air has been measured by installing a pitot tube at air cross section. Also air density has been calculated by employing ideal gas relation and measuring output dry bulb temperature and atmosphere pressure. Wet and dry bulb temperatures have been measured by a turning psychrometer. Also output dry air temperature of mixer box shouldn't exceed defined amount (a maximum of ±5.1°C) during tests [2]. As evaporative coolers standards, aeration amount has been measured at constant triggering condition and turned off pump by a pitot tube [3]. Constant triggering condition is obtained when measured temperature doesn't change more than 5.0°C within 15 seconds.

Cooler evaporation efficiency test is done based on measurements of input dry and wet bulb and also output dry bulb temperatures in standard and stable conditions.

Propeller and motor revolutions are measured by optical tachometer (Stroboscope) directly; in this method in the sake of motor revolution measurement a gap has been chapped on the body and also in the sake of propeller revolution measurement main mesh has been changed with a transparent mesh.

III. EFFECTIVE PARAMETERS IN FAN PERFORMANCE, ENERGY CONSUMPTION AND COOLER OPERATION

Crossing air flow rate for all coolers with equal capacity has been drawn on separate charts. Although these charts illustrate coolers' efficiency in general, because of using motors with different powers it's not possible to compare them truly with regard to either turbomachine or energy consumption efficiencies. Therefore, they haven't been brought in this paper.

Non-dimensional flow coefficient is an important effective parameter to compare different fans efficiencies on a cooler. This non-dimensional parameter includes effects of fan speed and diameter. So in comparison with crossing air chart it has the advantage of comparing turbomachine effectiveness.

$$\text{Non-dimensional flow coefficient: } Q/ND^3$$

where, Q is cooler volumetric flow rate in cubic meter; N is fan high revolution in revolution per second; D is fan average diameter.

Nasser Ghassembaglou is with the Mechanical Engineering Department, Istanbul Technical University, İnönü Caddesi, No. 65 Gümüşsuyu 34437 Beyoğlu, Istanbul, Turkey (corresponding author to provide phone: 539-611-8739; e-mail: ghassembaglou@itu.edu.tr).

Leila Torkaman is with Institute of Standards & Industrial Research of Iran (ISIRI), Tabriz, East Azerbaijan, Iran (e-mail: torkamanl@yahoo.com).

Cooling efficiency which shows evaporative cooler straw efficiency is strongly affected by input air humidity; because of providing a narrow span of relative humidity (wet bulb temperature) in cooler performance standards, measuring this efficiency in same cooler will give different results in different days and conditions. Because of calculation in formula and inserting sensible cooling directly, cooling efficiency doesn't have a direct affection on energy consumption efficiency, but a little on EER.

Like flow coefficient, non- dimensional head coefficient is an effective parameter in turbomachine efficiency assessment too. A turbomachine efficiency is a function of its head and flow coefficients and also its geometrical parameters which is proportion of length to fan diameter.

Non- dimensional head coefficient: gH/N_2D_2

where, g is gravity in meter per square seconds; H is fan head in meter

With regard to Ratto characteristics in turbomachines power, coefficient is calculated by multiplying flow coefficient by head coefficient as following:

$$\lambda = \frac{gHQ}{N^3D^5} \tag{1}$$

Energy efficiency ratio is important in cooler performance definition and has an effective role in energy consumption which is defined as division of sensible cold produced by cooler to its consumed energy. This ratio is the major factor in designing energy label.

Cooler sensible cooling amount is calculated as:

$$SH = \rho.Q.Cp(t_{di} - t_{do}) \tag{2}$$

where, SH is cooler sensible cold in kj/s; C_p is air specific heat in kj/kg.K; t_{di} is dry bulb temperature in ^oC; t_{do} is output dry bulb temperature in ^oC; ρ is air specific mass in kg/m^3

IV. MODELING

One of reputable thermodynamic models in background of direct evaporative coolers is Hwang numerical model [4]. This model gets input dry bulb temperature and input humidity ratio and by application of psychrometric relations and an experimental relation in calculating convectional heat transfer coefficient, predicts output temperature. It should be mentioned that in this model input values are dry and wet bulbs temperatures, and this model is a comprehensive one which in addition to thermodynamic properties calculations, calculates geometrical and fluid performance too.

Provided model for coolers encompasses three coupled parts as:

1. Thermodynamic modeling of evaporative cooler to obtain cooler output air properties, evaporation efficiency, evaporative consumption and sensible cooling capacity
2. Statistical modeling to obtain cooler aeration
3. Statistical modeling to obtain cooler energy consumption

With regard to requirements of Reynolds and Prandtl definitions in cooler equations, some properties such as viscosity and air convectional heat transfer coefficient should be defined as some relations. Demanded relations for these properties are obtained by fitting curves on inserted values in air properties table. This job has been done by EES software.

Achieved equations of fitting curves are as:

$$\mu = 9.8066 * 10^{-6}(1.712 + 0.0058T) \tag{3}$$

where, T is air dry bulb temperature in ^oC; μ is viscosity in kg/m.s.

$$K = 7.691 * 10^{-5}T + 2.4178 * 10^{-2} \tag{4}$$

where, K is air heat conduction coefficient in w/m.K.

Finally non-dimensional Prandtl and Reynolds numbers are defined as:

$$\mathrm{Re} = \frac{\rho.V.L_C}{\mu} \tag{5}$$

$$\mathrm{Pr} = \frac{Cp.\mu}{k} \tag{6}$$

In mentioned equations C_p is air specific heat which is approximately constant in intended bounds (1.008 kj/kg^{o}K) and LC is characteristic length which is calculated as:

$$LC = \sqrt{\frac{A}{L1 * L2}} \tag{7}$$

where, L_1 and L_2 are cooler bottom dimensions in meter; A is lateral effective area in square meter; LC is characteristic length.

In thermodynamic part of model, psychrometric and experimental relations are used. In this section all required physical and thermodynamic properties have been calculated. Next step is to calculated air properties at output. With regard to air adiabatic saturation process through the cooler, wet bulb temperature is constant. In this level it's possible to obtain cooler evaporation efficiency and sensible cooling capacity as:

$$SH = \rho.Q.Cp(T - TT) \tag{8}$$

where, SH is cooler sensible cooling capacity in Watt; T is input air dry bulb temperature in ^oC; TT is output air dry bulb temperature in ^oC.

$$EE = \frac{T - TT}{T - T_w} \tag{9}$$

where, T_w is air wet bulb temperature in ^oC.

V. AERATION STATISTICAL MODEL

To approach aeration real amount independent of test conditions with regard to performance and geometrics of cooler, it is needed to set a statistical model on the basis of analytical and experimental processes on numerical information related to tests on available different coolers which has the possibility of optimization [5]. In the sake of modeling important parameters should be firstly realized, then coupling between these parameters and aeration should be created, finally they should be compared with experimental test results in the sake of validation.

In this step, aeration is considered as a function of unknown coefficients and exponents of different parameters. It should be known how per parameter affects aeration amount.

Fig. 1 shows aeration amount changes with regard to propeller width. It is obvious that aeration is growing up with propeller width increment. Flow rate proportion to propeller width is less than one and curve is approximately horizontal near b_{max} point.

With regard to continuity rule flow rate is proportional to flow cross section which is calculated with propeller average diameter [6].

$$Q = A.V = \pi DbV \tag{10}$$

In turbomachines flow angles are generally defined tangential on basis of propeller circumference which has practical values of 10 to 35 degrees for input flow and 30 to 70 degrees for output flow. As this result they are defined as sinusoidal values in model.

Propeller blade numbers is effective in head flow production and domination to flow friction at channel; in application blade numbers is directly related to propeller diameter and consequently to air flow rate. However, blade numbers increment has an optimized number which because of friction resistance in propeller will decrease flow rate if exceeded [7].

Propeller revolution has a direct relation with aeration, because air speed will increase linearly with its increment; so as Fig. 4 revolution function is defined as 1 in modeling.

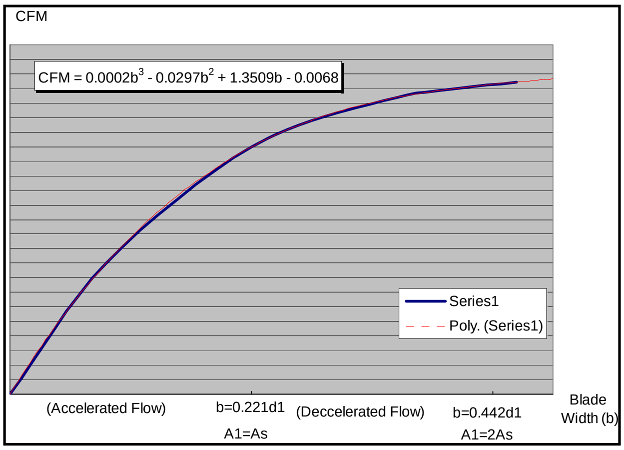

Fig. 1 Aeration changes on propeller width

Effective lateral area actually is a free area for air cross at cooler input. Therefore, increment of this area will increase aeration amount. With regard to Linearization efforts in experimental curve fittings it is necessary to increase variables in model equation. Therefore, two terms as propeller diameter multiplied to its width and propeller diameter multiplied to its revolution have been added to model. Also a constant term has been added to model equation which represents similar items (like straw density) effects in all coolers.

With regard to unknown variables, eleven coolers have been chosen among all coolers to solve the model. By entering coolers' specifications eleven equations with eleven unknown variables have been obtained which solved by Engineering Equation Solver (EES).

By solving these equations and achieving unknown coefficients a general shape of test model is obtained which shows cooler aeration on basis of its geometrical and physical specifications; this is possible to test it with other coolers information.

$$\begin{aligned} Q = {} & A_1 B.D + a_2 \sin(100-\theta_1) + a_3 n + a_4 D.RPM + a_5 RPM + a_6 A^{0.7} + a_7 .\sin(130-\theta_2) \\ & + a_8 B^{0.9} + a_9 A^{0.5} + a_{10} D + a_{11} \end{aligned} \tag{11}$$

where, B is propeller width in millimeter; θ_1 is propeller input angel relative to radius in degrees; θ_2 is propeller output angel relative to radius in degrees; n is propeller blade number; RPM is propeller revolution in radian per minute; A is lateral effective area in square meter.

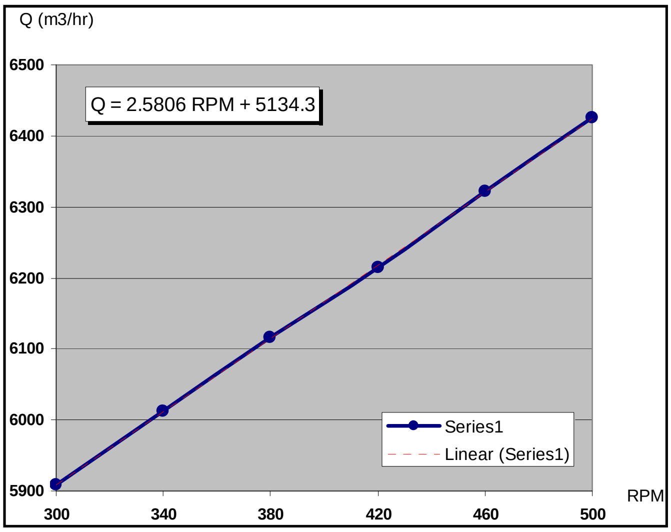

Fig. 2 Propeller revolution effect on aeration amount

After solving equations, coefficients have been calculated as shown in Table I:

TABLE I
AERATION MODEL COEFFICIENTS

a_1= -0.183	a_2= 6659.967	a_3= -2.276
a_4= 0.076	a_5= 31.067	a_6= -0.348
a_7= -984.372	a_8= 73.914	a_9= 17.705
a_{10}= 154.378	a_{11}= -48231	

Mentioned statistical model has a very good precision and its average deviation is about 3 percent. It should be mentioned that these coefficients aren't non-dimensional and their unit can be obtained for each one by dividing flow rate unit (m^3/h) to the coefficient term unit.

VI. COOLER ENERGY CONSUMPTION STATISTICAL MODEL

It's necessary to model energy consumption in the sake of EER modeling.

Motor size will have a direct affection on energy consumption and is inserted as motor rated power. As this result, its initial power is considered as one in model and its real value is obtained by trial and error.

Another parameter is pulleys' diameter proportion; by considering motor pulley diameter as DPM and propeller pulley diameter as DPF mentioned parameter will be $\frac{DPM}{DPF}$.

Other important parameter is belt efficiency; belt efficiency is its output energy to input energy proportion; because of sliding its efficiency is less than 100 percent. Therefore:

$$\eta_B = \frac{\frac{MRPM}{FRPM}}{\frac{DPF}{DPM}} \tag{12}$$

Cooler aeration amount is inserted into energy consumption model as a criterion which contains all geometrical parameters. Most important factors to increase aeration are propeller speed and its size. Both of these factors cause to more energy consumption.

Because of their importance, angels are calculated in model too. To prevent model vagueness on $\theta_1=0$, it's replaced by $\sin(\theta+1)$; it's not necessary for θ_2 because there is no cooler with output angel of zero.

By increasing lateral effective area energy consumption grows up too; but this increment isn't permanent and curve becomes saturated.

Increment of air driver altitude which is inserted into model by its proportion to output channel altitude, results in energy consumption increment; this is a result of resistance increment in output air cross section.

To include other parameters which is not encompassed in model and also simplification errors, a constant has been added to model which is calculated by solving equations.

There are 6 unknown variables in obtained model; then 6 coolers with highest and lowest energy consumptions have been selected among eleven coolers which had been used at former model solution. In the sake of solving equations, EES software has been used.

Finally after so many analysis, error probations and unknown parameters changes, following model has been obtained for energy consumption:

$$W = b_1 \frac{Q^3}{\sin(\theta+1)} . \eta_B + b_2 \frac{Q^3}{\sin\theta_2} . \eta_B + b_3 HP^{0.8} + b_4 A^{0.7} + b_5 [\frac{h_{gu}}{h_{ch}}]^{0.8} + b_6 \tag{13}$$

where, θ_1 and θ_2 are propeller input and output angels relative to radius in degrees; FRPM is propeller revolution in radian per minute; MRPM is motor revolution in radian per minute; DPF is propeller pulley diameter in millimeters; DPM is motor pulley diameter in millimeters; HP is motor rated power in horse power; h_{gu} is air driver altitude in millimeters; h_{ch} is air output channel altitude in millimeters.

After solving equations, unknown coefficients are calculated as are shown in Table II.

TABLE II
AERATION MODEL COEFFICIENTS

b_1= 6.603e-11	b_2= 1.274e-8	b_3= 186.604
b_4= -59.443	b_5= 2.015	b_6= 457.9

VII. COMPREHENSIVE MODEL CREATION BY MIXING MODELS

After realizing parameters and creating relations between them and also presence of aeration, energy consumption and output air temperature, it is possible to calculate EER parameter which is comparative and all optimizations will be done on it.

VIII. ENERGY LABEL

Table III shows each cooler rating with regard to its EER. It's good to mention that number 65 has been selected as maximum number on the basis of researches and optimizations.

TABLE III
AERATION MODEL COEFFICIENTS

$EER \geq 65$	→1A
$58 \leq EER < 65$	→2B
$50 \leq EER < 58$	→3C
$42 \leq EER < 50$	→4D
$34 \leq EER < 42$	→5E
$26 \leq EER < 34$	→6F
$EER < 26$	→7G

Inspection of all coolers shows their rating between 6 and 7; therefor it's demanded to optimize them in the sake of energy consumption reduction.

IX. OPTIMIZATION

Intended function in optimization is EER which should be maximized. EER increment is possible by aeration increment, increment of produced air temperature difference and energy consumption decrement.

Output air and sensible cooling capacity are complicated functions of input properties in thermodynamic model, so Lagrange Coefficients method is not suitable here. Therefore, every variable has been changed in applicable range and its effect on EER has been inspected. Finally by collecting all inspections best solutions in the sake of EER increment are provided.

Following sections inspects different parameters effects on aeration, energy consumption and EER in a random cooler by applying obtained numerical model.

A. Effects of Propeller Pulley Diameter

Figs. 3-5 show effects of propeller pulley diameter on aeration, energy consumption and EER respectively. In these charts motor pulley diameter has been considered as 71.5 mm which is used in normal coolers.

Increment of propeller pulley diameter decreases its revolution speed and aeration amount. Meanwhile, because of constant motor torque, propeller revolution decrement decreases cooler energy consumption. This increases EER to 32.5 from 17.5; therefore, propeller pulley diameter should be increased to its highest possible size; but aeration decrement should be considered in this process as a negative effect.

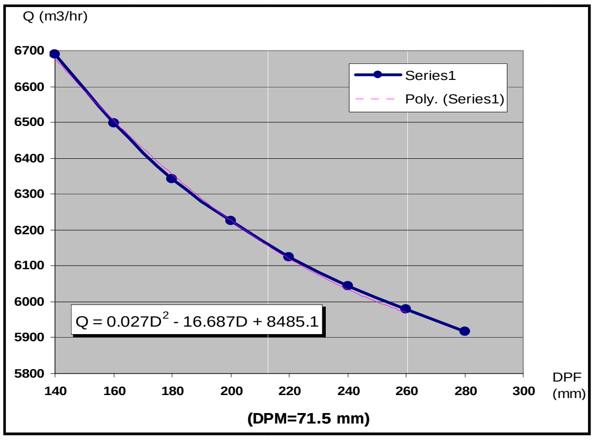

Fig. 3 Effects of propeller pulley diameter on aeration

B. *Effects of Motor Pulley Diameter*

Motor pulley diameter increment results in propeller revolution speed growth which increases aeration amount as shown in Fig. 6. In this situation, more power is needed to turn propeller as is obvious in Fig. 7. This results in EER decrement as shown in Fig. 8.

In the sake of consistency, for all of these charts propeller pulley diameter is considered as 245 mm. Therefore, motor pulley diameter should be selected as its least possible amount; again aeration decrement should be considered here.

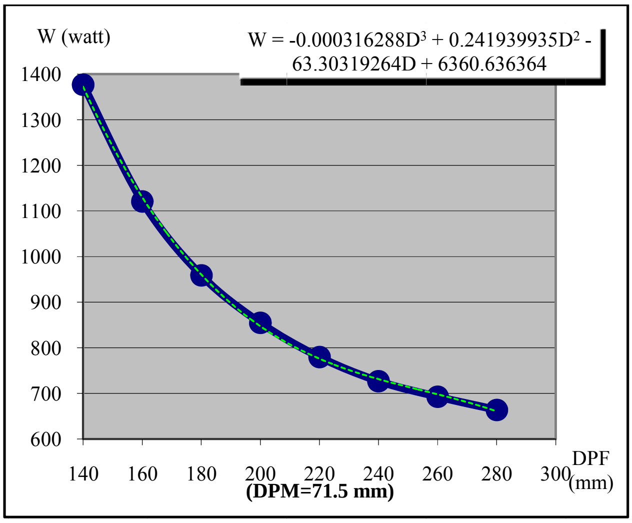

Fig. 3 Effects of propeller pulley diameter on energy consumption

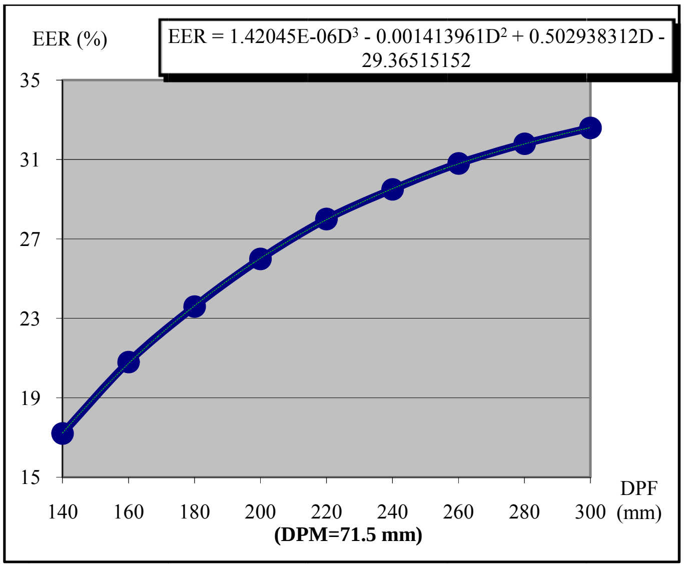

Fig. 4 Effects of propeller pulley diameter on EER

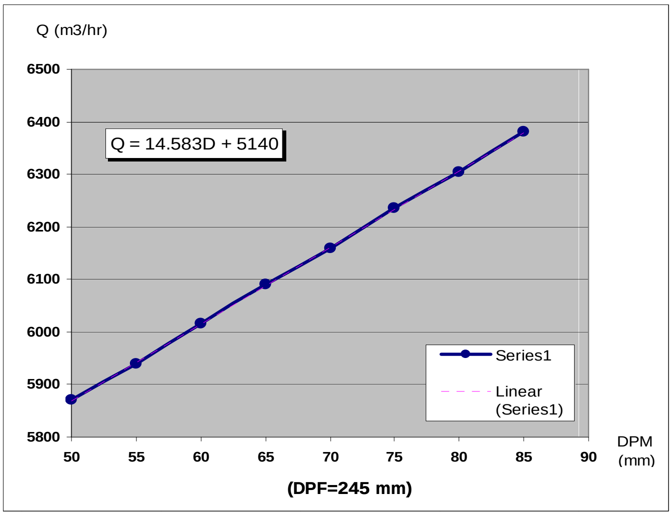

Fig. 5 Effects of motor pulley diameter on aeration

C. *Effects of Lateral Effective Area*

Fig. 9 shows effects of lateral effective area on aeration amount. It’s obvious that lateral area increment through a limited size (about 1.1 m^2) increases aeration amount.

Effects of lateral effective area on energy consumption are as like as aeration; but as these tests have been done reticulated and without pomp, so energy consumption chart hasn’t provided here.

Fig. 10 shows EER increment by lateral area growth. As this chart shows, to increase EER, lateral area should be increased to its highest possible amount. But, evaporation effectiveness decrement should be considered as a negative effect of this process which increases output dry bulb temperature. Here EER changes domain is about 4 units.

D. Effects of Propeller Weight Decrement

Propeller weigh decrement results in lower energy consumption and higher EER which is possible by using polyethylene propeller.

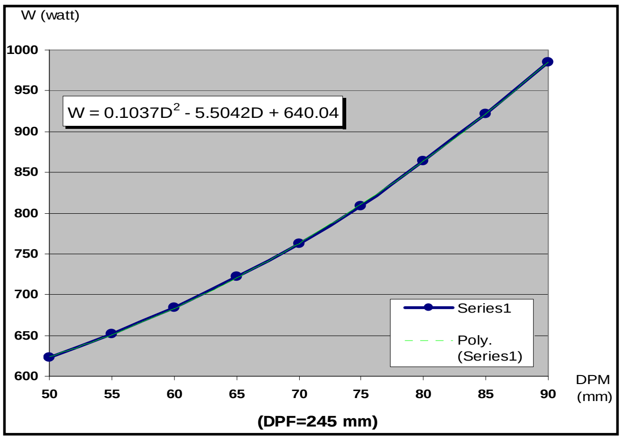

Fig. 6 Effects of motor pulley diameter on energy consumption

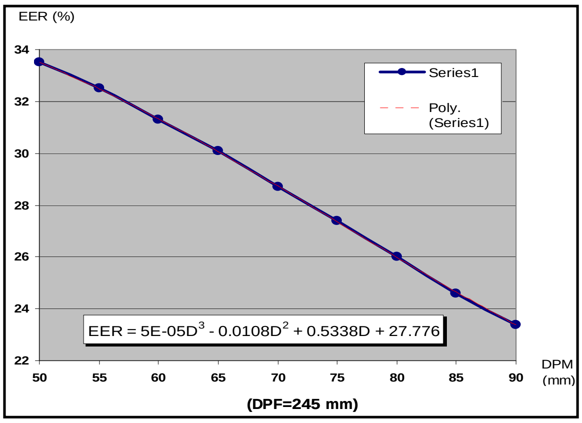

Fig. 7 Effects of motor pulley diameter on EER

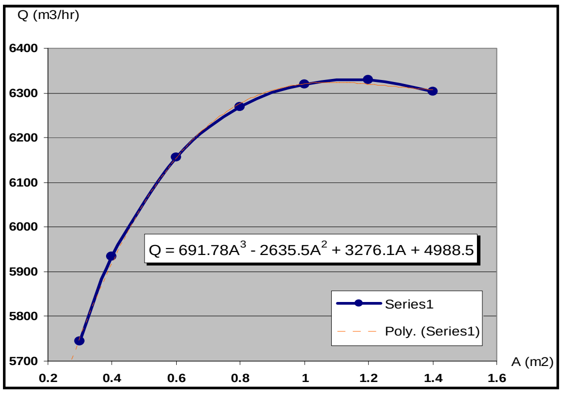

Fig. 8 Effects of lateral effective area on aeration

X. GENERAL OPTIMIZATION

First model which is used in optimization had a 62.5 mm of motor pulley diameter and 245 mm of propeller pulley diameter.

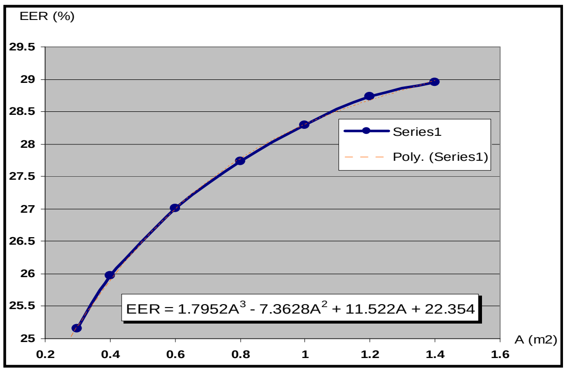

Fig. 9 Effects of lateral effective area on EER

Optimization steps are shown in Table IV briefly.

Aeration model results with 6103 m^3 aeration, 774 watt power and an EER of 44 are very close to experimental results.

First step in optimization is to increase motor effectiveness which has a great effect on EER and raises its level from D to C.

Second step is to alter metallic propeller with a polyethylene one which decreases energy consumption to 96% of normal usage and raises EER from C to B.

Third step is to increase propeller pulley diameter to 280 mm which results an EER growth of 1.91.

Fourth step is to decrease motor pulley diameter to 50 mm which results in an EER growth of 2.556.

And last step is to increase lateral effective area which raises EER to its highest amount of 65.126; in this situation, EER level is raised to A.

TABLE IV
OPTIMIZATION STEPS

Step	Changes	Q (m^3/h)	W	EER
0	-	6103	774	44
1	Motor effectiveness increment from 48% to 61% by changing it	6103	609	55.91
2	Propeller weight decrement	6326	585	59.91
3	Propeller pulley increment to 280 mm	6238	523	61.82
4	Motor pulley diameter decrement to 50 mm	6055	464	64.28
5	Lateral effective area increment to 1.2 m^2	6080	460	65.126

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