EVALUATION OF FAN MODELS FOR APPLICATION TO ECM FAN/MOTOR COMBINATIONS

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ABSTRACT
Electronically commutated motors are applied to drive the fans in fan powered terminal units for variable airflow applications. Two fan models used to characterize larger commercial variable speed fans were evaluated to determine if they could be applied to model electronically commutated fan/motor combinations used in fan powered terminal units. These models included those by Clark (1985) and Stein and Hydeman (2004). Four manufacturers provided detailed performance data on 36 fan/motor combinations that were used in commercially available series and parallel fan powered terminal units. All of the fan motors were electronically commutated motors with motor sizes ranging from 0.33 to 1 hp (249 to 746 W). The data included airflow, power, and power factors that were measured over a range of static discharge pressure from 0.1 to 0.75 in w.g. (25 to 187 Pa).

Both fan models correlated performance data of individual fan/motor combinations. However, neither model was able to provide a generalized method to satisfactorily correlate the wide range of provided by the manufacturers. In addition, the performance data for some of the smaller fan/motor combinations showed considerable variation at lower controller settings than the data at higher controller settings. A new model was developed that provided a better correlation for the fan/motor performance data. This model could be used by building simulation modelers seeking a generalized model of ECM fan/motor performance for applications in fan powered terminal units.

INTRODUCTION
Variable air volume (VAV) systems maintain the zone thermal comfort by varying the conditioned air supplied to the zone. A central air handler unit (AHU) delivers air through a duct system to VAV terminal units that control the airflow based on the zone load. A terminal unit with a fan is called a fan-powered terminal unit (FPTU). FPTUs mix primary air from the AHU with recirculated air from the plenum space. Supplemental heat can be provided when needed to the air by a heating coil.

In recent years, electronically commutated motors (ECMs) have begun to be used to drive the fans in FPTUs. A DC voltage controller is used to vary the speed of the motor and the amount of airflow from the fan. For a variable airflow application, the ECM can be tied into a building automation system to provide the desired airflow to meet the zone load.

The purpose of this paper was to evaluate existing fan models that have been used to characterize larger commercial fans and determine if they can be applied to the ECM fan/motor combinations used in FPTUs. Models by both Clark (1985) and Stein and Hydeman (2004) were evaluated using ECM fan/motor performance data from FPTU manufacturers. A new model was developed based on the Stein and Hydeman (2004) model that included a “pseudo” pressure ratio term to correlate fan/motor efficiency data. The model should provide building simulation modelers with a simple non-dimensional model to characterize ECM fan/motor performance for applications in fan powered terminal units.

PRIOR WORK
Clarke (1985) originally published his model as a part of the reference manual for the public domain simulation model called HVACSIM+. The model included a dimensionless flow coefficient, $\phi$, and pressure coefficient, $\psi$. The fan efficiency was modeled as a fourth degree polynomial:

$$\eta_{fan} = a_1 + a_2\phi + a_3\phi^2 + a_4\phi^3 + a_5\phi^4$$  (1)

Where:  
$a_1$, $a_2$, $a_3$, $a_4$, and $a_5$ were regression coefficients.

The non-dimensional flow coefficient, $\phi$, was:
The fan efficiency could be fit to the flow coefficient data and then used to estimate the power of the fan:

\[ \phi = c_1 \frac{Q_{\text{flow}}}{N D^3} \]  \hspace{1cm} (2)

where:
- \( c_1 \) = constant
- \( Q_{\text{flow}} \) = fan airflow in ft³/min (m³/s)
- \( N \) = fan speed (rpm)
- \( D \) = fan diameter in ft (m)

The model was developed based on the ideal fan affinity laws. For example, the airflow should be proportional to 1/(ND³), which is in the denominator of the flow coefficient in Equation 2. No explanation was provided on the origin of this model by Clarke (1985). Given that the efficiency was used in a standard calculation of fan power, it would appear that either fan static efficiency or fan total efficiency could be used as long as the corresponding static or total pressure was used in Equation 3. Because the fan diameter and speed were a part of the non-dimensional flow coefficient, it was hoped that this model could normalize the performance of different sizes operating at different speeds.

The Clarke (1985) model was in a list of component models published in the ASHRAE HVAC 2 Toolkit (Brandemuehl 1993). Wang et al (2004) proposed using the model for estimating a fan’s contribution to total energy use in commercial buildings. They also had separate models for the fan motor, driveshaft, and inverter. Their application was primarily to large central air handlers. Kimla (2009) and Li et al (2010) applied this model to air handlers and cooling tower fans. These uses of the Clarke model focused on the performance of larger fans and not to the smaller fan/motor combinations found in FPTUs.

Stein and Hydeman (2004) developed a fan model to for a wide range of fan types and sizes. It could estimate fan system energy over a range of operating conditions and was simple to integrate into a building simulation model. Their focus was also on larger fans. In their model, a system curve coefficient (SCC) was first calculated:

\[ \text{SCC} = \frac{\Delta P_{\text{static}}}{Q_{\text{flow}}} \]  \hspace{1cm} (4)

The SCC is a curve that passes through the origin and is along a line of constant fan efficiency. The fan efficiency is determined from manufacturer’s data:

\[ \eta_{\text{fan}} = \frac{Q_{\text{flow}} \Delta P_{\text{static}}}{P_{\text{fan}}} \]  \hspace{1cm} (5)

In the paper, the above equation was written in IP units and it has been generalized here so either IP or SI units can be used. Manufacturer’s data can be used in Equations 4 and 5 to calculate both SCC and \( \eta_{\text{fan}} \). Because the \( \Delta P_{\text{static}} \) in Equation 4 is small and the airflow is a large number in IP units, the resulting values of SCC in IP units was very small – on the order of 10⁻³ to 10⁻⁴. To better visualize the results, Stein and Hydeman (2004) created another term, gamma, defined as:

\[ \gamma = -\ln(\text{SCC}) \]  \hspace{1cm} (6)

When plotted against either SCC or \( \gamma \), the efficiency showed a distinct peak. The authors also provided a third-order regression to fit the fan efficiency to gamma. They found that this approach was applicable for six types of fans: plenum, backward inclined, airfoil, mixed flow, propeller, and vane-axial with fixed blades. Equation 6 is an unusual formulation because the logarithm is performed on SCC which is not dimensionless but has units of (in w.g)/(ft³/min)³ in IP units or Pa/(m³/s)² in SI units.

Because both the Clarke (1985) and the Stein and Hydeman (2004) models are generic models, we wanted to see if they could be applied to the smaller fan/motor combinations found in FPTUs. The fans are typically forward curved blade fans integrated into a fan/motor assembly. In larger air handlers, the fan is tested separately from the motors. In FPTUs, the two are tested together because the fan motor sits inside the fan squirrel cage. Building simulation software, such as EnergyPlus (2013), still treats the fan/motor combinations in FPTUs the same way that large air handlers are treated. The user is expected to input fan and motor characteristics separately. Because these data are not available separately for ECM fan/motors, building energy models can be tempted to use the default value for fan efficiency in EnergyPlus (2013) as well as static pressures, both of which are much larger than the typical values found in FPTU fans and motors. There is a need to provide a model and data that better match the actual performance of ECM fan/motor combinations in FPTUs.

**FPTU ECM FAN/MOTORS**

ECM fan/motor performance data from 36 units were provided by four manufacturers that are identified as manufacturers A, B, C, and D in the tables and figures below. The fan/motor assemblies were from FPTUs at various combinations of cabinet sizes, cabinet styles.
(underfloor or overhead), and cabinet profiles ("low" and "standard"), with motor sizes ranging from from 0.33 hp (249 W) to 1 hp (746 W). Each cabinet design potentially produces different flow conditions entering the FPTU fan, which could generate differing air system effects that impact the overall fan performance. Also, two dual fan/motor assemblies were provided with 0.33 hp (249 W) and 0.75 hp (560 W) motors respectively. Considering the variety in terms of motor sizes and cabinet designs, the 36 assemblies should cover the typical fan/motor combinations in FPTUs in field applications.

Performance data were collected by manufacturers in their own laboratories and provided to the authors through a representative of the Air Conditioning Heating and Refrigeration Institute (AHRI) so that the identity of the manufacturer remained anonymous. Manufacturers were asked to provide both descriptive (see Table 1) and performance data (see Table 2) on each fan/motor combination. In Table 2, the settings on the controllers were specified in DC voltages (typically from 0 to 10 V) or in percentages from 0 to 100%. Each manufacturer performed measurements at the ECM controller settings that they normally test their equipment. Thus, the ECM controller settings varied from manufacturer to manufacturer.

Table 1 – Descriptive data for FPTU and fan/motor combinations

<table>
<thead>
<tr>
<th>Item</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan Model Number</td>
<td></td>
</tr>
<tr>
<td>Series or Parallel FPTU Application</td>
<td></td>
</tr>
<tr>
<td>Primary Inlet Diameter</td>
<td></td>
</tr>
<tr>
<td>Design range of airflow of FPTU</td>
<td></td>
</tr>
<tr>
<td>Recommended operating pressures</td>
<td></td>
</tr>
<tr>
<td>Maximum recommended airflow</td>
<td></td>
</tr>
<tr>
<td>Minimum recommended airflow</td>
<td></td>
</tr>
<tr>
<td>Fan manufacturer</td>
<td></td>
</tr>
<tr>
<td>Motor manufacturer</td>
<td></td>
</tr>
<tr>
<td>Motor Size</td>
<td></td>
</tr>
<tr>
<td>Fan discharge dimensions</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Detailed measured performance data on each FPTU fan/motor combination

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM Setting</td>
<td>voltage or value</td>
</tr>
<tr>
<td>discharge static pressure</td>
<td>in w.g. (Pa)</td>
</tr>
<tr>
<td>Airflow</td>
<td>ft³/min (m³/s)</td>
</tr>
<tr>
<td>Current</td>
<td>Amps</td>
</tr>
<tr>
<td>volt-amps</td>
<td>volt-amps</td>
</tr>
<tr>
<td>power factor</td>
<td>-</td>
</tr>
<tr>
<td>power</td>
<td>W</td>
</tr>
<tr>
<td>motor speed</td>
<td>rpm</td>
</tr>
<tr>
<td>power/airflow</td>
<td>W/(ft³/min) W/(m³/s)</td>
</tr>
</tbody>
</table>

An identification procedure was developed for reporting each fan/motor combination. Because all of the fan motors in this paper were ECMs, all designations start with “ECM”. The rated fan motor size, in horsepower, was converted to its decimal equivalent and multiplied by 1000. For example, the identification of a 0.5 hp (373 W) unit would be 0.500 multiplied by 1000 to give a value of 500. A 0.5 hp (373 W) fan/motor from manufacturer A was identified as ECM-500A. If a manufacturer had more than one fan/motor combination of the same size, such as manufacturer B had for 0.5 hp (373 W), then the first fan/motor was identified as ECM-1000B1 and the second as ECM-1000B2. For cases where there were dual fan/motors in a FPTU, the unit was identified with a 2x before the unit size. For example, the first 0.75 hp (560 W) from manufacturer A would be designated as ECM-2x750A1.

Figure 1 shows the power versus airflow data for the fan/motor ECM-750A2. For a given static pressure, the power decreased nonlinearly as the fan airflow dropped from about 2,000 ft³/min (0.94 m³/s) down to 500 ft³/min (0.24 m³/s). Along a given constant static pressure curve, the fan affinity laws would predict that the fan power would be a function of the cube of the airflow, which is consistent with the shape of the curves shown in Figure 1. For a constant airflow, the power increased as the static pressure increased. It should be noted that not all fan/motors showed the same uniform trends seen in Figure 1. In some cases, the lines of constant static pressure crossed. However, this figure illustrates the trend shown by many of the units.
Figure 2 shows fan/motor static efficiency as a function of fan static pressure and airflow. The static efficiency increased as the static pressure increased for a given airflow. The static efficiency decreased as the airflow increased for a given static pressure. Figure 2 also illustrates that the static efficiency varies significantly with both static pressure and airflow. At the least efficient operating condition, which is at the highest airflow and lowest static pressure, the static efficiency was as low as 5%. At the most efficient operating condition at lowest airflow and highest static pressure, the static efficiency could be over 30%. The highest operating static pressure for the fan/motor assemblies was 0.75 in w.g. (187 Pa). Laboratory measurements conducted by Bryant and Bryant (2015) found that static pressures across the fan in a series FPTU ranged from 0.128 to 0.246 in w.g. (31.9 to 61.3 Pa). Thus, FPTU fans may operate more often at the lower end of the static pressure range in Figure 2 rather than the upper end.

While building simulation programs like EnergyPlus require the user to choose a single efficiency for operation of an ECM fan/motor, Figure 2 demonstrates the difficulty of specifying a single efficiency over the entire expected operating range by showing that efficiency is dependent on both static pressure and airflow rate. Because static pressures and airflows change in a VAV system to meet the varying zone load, choosing a single “correct” efficiency may be difficult. Restricting the user to choosing one value applicable to the whole range of operating conditions of a FPTU may introduce significant errors in modeling an ECM FPTU.

CLARKE MODEL EVALUATION

The ECM fan/motor data were processed using the Clarke (1985) model. Figure 3 shows the fan/motor static efficiency versus the Clarke airflow coefficient for five fan motors in the range of 0.75 to 1.0 hp (560 to 746 W). The static efficiency decreased with airflow coefficient. For a particular fan/motor combination, the static efficiency could be modeled as a function of the airflow coefficient by fitting the data into the Clarke model. However, no generic model could be developed based on the Clarke model. For example, for a flow coefficient of 3.0 in Figure 3, the static efficiencies varied from approximately 3 to 33%, depending on the specific fan/motor combination. Thus, it would appear the Clarke (1985) model, as originally formulated, provides only a limited tool for characterizing the fan/motor combinations in FPTUs.

When plotting the data for the Clarke (1985) model, some of the units with smaller motor sizes showed a consistent trend to what is shown in Figure 4 for unit
ECM-333D3. At higher ECM settings (typically over 35% of the maximum setting on the controller), the data showed the same trends for the larger fan/motor units as was shown in Figure 3. At the lower ECM settings, the data deviated significantly from that at the higher settings. O’Neal et al (2015) saw similar trends in part load data for some ECM fan/motor combinations. Because the power data provided by manufacturers are for fan/motor combinations and not just fans, it is possible that the power use of the controller may impact the static efficiency results. For units with smaller motors at lower speeds, the fan power consumption is relatively small (~15 to 25 W). One manufacturer who made measurements of one controller found that the power consumption of the controller was about 7 W for a 0.5 hp (373 W) motor. The trends shown in Figure 4 were similar to the results of all of the 0.33 hp (246 W) and 0.5 hp (373 W) fan/motor combinations. If the results from the lower ECM settings are eliminated from the data sets, then the plots look similar to those for the larger fan/motor combinations shown in Figure 3.

Figure 4 Static efficiency versus flow coefficient for fan/motor combination ECM-333C3.

STEIN AND HYDEMAN MODEL EVALUATION

The fan/motor data were processed by using the Stein and Hydeman (2004) model. Figure 5 shows a plot of fan/motor static efficiency versus gamma for seven of the 0.75 hp (560 W) fan/motor combinations from three manufacturers. We have plotted gamma as if it does not have units even though it contains a logarithm of variables that do have units. The static efficiencies increased with decreasing gamma for each fan/motor combination. As with the Clarke (1985) model, the data points for an individual ECM fan/motor could be fit with a non-linear curve. Unlike the fans in Stein and Hydeman (2004) paper that had a distinct peak, none of these units showed a peak in efficiency. All fans appeared to asymptotically approach a maximum static efficiency between 35 and 40%. Compared with the results shown in Figure 3, Figure 5 indicates that the Stein and Hydeman model provided a better job of compressing the data from different fan/motors. For example, at a gamma of 15, the fan/motor efficiency only varied from approximately 10 to 33%. By contrast, the spread in the data for the Clarke model varied from 3 to 33% for a flow coefficient of 3. Some of the compression may be due to the fact that gamma is a logarithmic function. Although an improved representation was observed in Figure 5, it would still be difficult to use the Stein and Hydeman (2004) model to capture the entire static efficiency performance over a wide range of ECM fan/motor combinations given the fact that Figure 5 only included units with 0.75 hp (560 W) fan motors. Even for the results with one single size motor, considerable efficiency variations were observed for a given gamma value.

Figure 5 Static efficiency versus gamma for the 0.75 hp (560 W) fan/motor combinations.

As with the Clark model, all of the 0.33 hp (248 W) and 0.50 hp (373 W) fan/motor combinations showed significant deviations at the ECM settings below about 33% of the maximum setting for the controllers. Figure 6 shows static efficiency results for three units with 0.33 hp (248 W) fan motors for the purpose of illustrating the issue at the lower settings.

Based on Figure 5, it would be appear that for an individual fan/motor combination, the Stein and Hydeman (2004) model can be used to estimate the static efficiency. However, given the wide variations in static efficiency versus gamma for the fan/motor units, it would difficult to use it as a general model.
DEVELOPMENT OF NEW MODEL

Even without the issue in the static efficiency data at the low ECM settings, both the Clarke (1985) and Stein and Hydeman (2004) models are not able to provide a generic model that allows a modeler to estimate the static efficiency for a wide range of fan/motor combinations. A number of possible variations of these models were considered. One that appeared promising is discussed below.

When considering the system curve coefficient (SCC) in Equation 4 that is a part of the Stein and Hydeman (2004) model, it seemed unusual that the developers did not non-dimensionalize SCC. Non-dimensionalization has the potential to bring possible geometric and other measured variables into a single non-dimensional variable that might better correlate the static efficiency. In SCC, the numerator is a pressure term while the denominator is a flow squared term. Flow squared is often associated with the velocity pressure in a duct system or fan. Thus, we looked at revising the denominator so that a velocity pressure of the air leaving the fan would be used instead of using the square of the airflow.

\[ P_v = \frac{\rho \left( \frac{Q_{flow}}{A} \right)^2}{2g} \]  \hspace{1cm} (7)

where:
- \( \rho \) = density of air
- \( A \) = cross sectional area = \( w \times D \)
- \( g \) = gravitational constant
- \( w \) = width of the fan
- \( D \) = diameter of the fan

The fan airflow, \( Q_{flow} \), is the same airflow used in the Stein and Hydeman (2004) model. The data on the fan/motor combinations included both single and double fans. Table 3 shows the range in the fan/motor data we analyzed. There was a wide range in airflows, motor sizes, and fan widths. The fan diameters only varied from 9 to 12.8 inches (22.9 to 32.5 cm). The fan static pressures ranged from 0.1 to 0.75 in w.g (25 to 187 Pa).

<table>
<thead>
<tr>
<th>Value</th>
<th>Motor Size</th>
<th>Airflow</th>
<th>Fan Diameter in cm</th>
<th>Fan Width in w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.33(248)</td>
<td>250 (0.12)</td>
<td>9(22.9)</td>
<td>2(5.1)</td>
</tr>
<tr>
<td>Max</td>
<td>1.0 (746)</td>
<td>4000(1.89)</td>
<td>12.8(32.5)</td>
<td>12.6(32.0)</td>
</tr>
</tbody>
</table>

After experimenting with different areas for Equation 7, it was decided to use an area that was formed by the product of the fan width (w) times the fan diameter (D) provided the best correlation for a wide range of the data. The SCC would then become a ratio of static pressure produced by the fan divided by a velocity pressure based on the airflow of the fan divided by area formed by the produce of w and D. Instead of using SCC, we defined this new term as the “pseudo” pressure ratio:

\[ P_r = \frac{\Delta P_s}{\rho_v} = \frac{\Delta P_s}{\rho \left( \frac{Q_{flow}}{A} \right)^2} = \frac{\Delta P_s}{\rho \left( \frac{Q_{flow}}{wD} \right)^2} \]  \hspace{1cm} (8)

This “pseudo” pressure ratio was then estimated for the fan/motor combinations over each unit’s range of static pressures and airflows. As with the Clarke (1985) and the Stein and Hydeman (2004) models, the static efficiency data at low ECM settings for units with 0.33 hp (246 W) and 0.50 hp (373 W) fan motors were problematic. The static efficiency data at these low ECM settings were eliminated from the data sets, and the fan/motor static efficiency was plotted against the pressure ratio. The result is shown in Figure 7. This figure includes data from eleven 0.33 hp (248 W), four 0.50 hp (373 W), seven 0.75 hp (560 W), and three 1.0 hp (746 W) fan/motor combinations. Not all of the 36 fan/motor combinations could be used. In some cases, only partial data sets were provided, which included two 0.33 hp (248 W), one 0.50 hp (373 W), and one 0.75 hp (560 W) fan/motor combination. Six other 0.33 hp (246 W) and one 0.50 hp (373 W) fan/motors combinations that had previously been identified as having problematic part load performance data by O’Neal et al (2015) were also not used here.
The data for the fan/motor static efficiency, $\eta_{fm}$, versus pseudo pressure ratio in Figure 7 were fit to the following logit expression:

$$\eta_{fm} = A_1 \left( \frac{1}{1 + e^{-(B_0 + B_1 \log_{10}P)}} \right)$$  \hspace{1cm} (9)

The constants in Equation 9 were given by:

$A_1 = 37$

$B_0 = -0.436$

$B_1 = 2.579$

While there was scatter in the data, we were surprised at how well the data grouped along the best fit line for the wide range of fan sizes. For someone modeling smaller fan/motor assemblies used in fan powered terminal units, Equation 9 could be used as a generic model for estimating the static efficiency. Considering that Equation 9 was developed based on 25 fan/motor assemblies from various combinations of motor sizes and cabinet configurations, the output from Equation 9 should be representative for many ECM FPTUs used in commercial buildings. It is important to note that the correlation in Equation 9 should not be used to estimate static efficiencies for units with a motor size smaller than 0.5 hp (373 W) at the ECM settings below about 35% of the maximum setting. While these data did not extend beyond a pseudo pressure ratio above 15, it is not recommended to use this correlation above that value.

**APPLICATION TO ENERGY MODELS**

The model developed here gives a researcher a generic model that allows them, with the right geometric and flow information on an ECM fan/motor combination to estimate the fan/motor static efficiency. In EnergyPlus (2013), both the fan and fan motor efficiency are expected to be input separately. The value coming out of Figure 7 and Equation 9 is the combined value of fan/motor efficiency. We would recommend using the value from Figure 7 as the fan efficiency and assume the motor efficiency is 100%. This product would give the same effective fan/motor efficiency as in Figure 7. EnergyPlus (2013) also requires the user to specify a pressure differential across the fan. In calculating the pseudo pressure ratio in Equation 8, the researcher will have used the static pressure differential and airflow that goes with the estimated fan/motor efficiency. From our discussions with FPTU manufacturers, it is important that a researcher use realistic fan static pressure differentials in both Equation 8 and in input to EnergyPlus. Fan static pressure differentials vary as the FPTU adjusts to the load in the zone. We have seen systems with fan static pressures operating near the low end (0.1 in w.g. (25 Pa)) of the data used in this study. Lacking any other data, a researcher should consider using 0.25 in w.g. (62 Pa). This value is used in the ANSI/AHRI (2011) test procedure for terminal units. All of the fan/motors used in this study operated at or less than a maximum static pressure of 0.75 in w.g. (187 Pa). Thus, the calculation procedure should never be used with static pressure higher than the maximum used here.

**SUMMARY AND CONCLUSIONS**

Two available fan models that were designed to estimate the performance of larger fans in commercial buildings were evaluated to determine whether they could be applied to the ECM fan/motor combinations used in commercially available fan powered terminal units. Results show that both the Clarke (1985) and Stein and Hydeman (2004) models were able to correlate the data well for an individual fan/motor combination. However, neither model could be used as a generic model to represent a large number of fan/motor combinations.

A variation of the Stein and Hydeman (2004) model was developed based on the data from 25 fan/motor combinations, which included a pseudo pressure ratio as the primary explanatory variable for predicting the static efficiency. The model should be applicable for most of the ECM fan/motor combinations found in fan powered terminal units. A user can estimate the fan static efficiency using the correlation, along with the knowledge of airflow, fan static pressure, and the width and diameter of the fan. It is important to note that the model should not be used to estimate static efficiencies for units with a motor size smaller than 0.5 hp (373 W) at the ECM settings below about 35% of the maximum setting. While these data used to
develop the new model cover a wide range of fan/motor applications in FPTUs, the model should be used with caution if applied beyond the range of the data that was used to develop it.

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