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Flow Observations in the Labyrinth Packing

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Abstract

The flow patterns in the labyrinth packing were investigated, based on the flow observations which were carried out by using a "smoke-tunnel". Moreover, these results are discussed in reference to my experimental data on the leakage loss through the labyrinth packing which was previously reported.

I Introduction

The author has studied experimentally the leakage loss of the air through the labyrinth packing of straight-throught type, especially the effects of the shape of the labyrinth packing.[1][2][3][4] In the results of these experiments, it has been shown that the leakage loss was the smallest when the pocket of the labyrinth packing was in form of a shallow rectangular groove. This is of advantage not only for the purpose of reduction of the leakage loss, but also from the view point of construction of the labyrinth packing. And in order to understand these results and to iufer their physical reasons, it would be of significance to study the flow patterns which take place in the pockets of the labyrinth. Although some reports on flow observation have come out[5], the water has usually been used as the flow medium. But in this experiment, the air was used as the flow medium, and the smoke was introduced to visualize the stream. The stream flowing through an enlarged model was observed and its photograph was taken. The influence of the shape and the size of the pocket of straight-through type labyrinth were mainly investigated. Moreover, as an additional work, observations of the flow through staggered type were also carried out.

II Experimental Apparatus

As the experimental apparatus for flow visualization, "smoke-tunnel" was used. The schematic diagram of "smoke-tunnel" is shown in fig. 1. The comprssed air derived from a compressor C is charged into a smoke producer S; the smoke is

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[1] K. Komotori, Trans. J. S. M. E. Vol. 21, No. 105, 1955, pp. 377/382

[2] K. Komotori, Trans. J. S. M. E. Vol. 21, No. 108, 1955, pp. 608/613

[3] K. Komotori, Trans. J. S. M. E. Vol. 22, No. 121, 1956, pp. 674/686

[4] K. Komotori, Trans. J. S. M. E. Vol. 23, No. 129, 1957, pp. 330/336

[5] C. Keller, Escher-Wyss News, Janu./Febru. 1934, pp. 9/13

produced here, then cleaned by passing through water *W*, gathered in the receiver *R*, and discharged from the "comb-type-nozzle" *N* into the "smoke-tunnel", while the air is inhaled from the left side by a blower *B*. At the middle of the tunnel, there is a glass observation window the area of which is 585mm×475mm and the cross section of this part is rectangular(475mm×30mm), where a two dimensional enlarged model *M* is set.

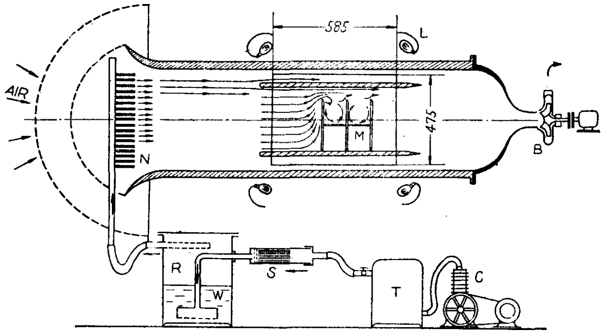


Fig. 1. Schematic Diagram of "Smoke-Tunnel"

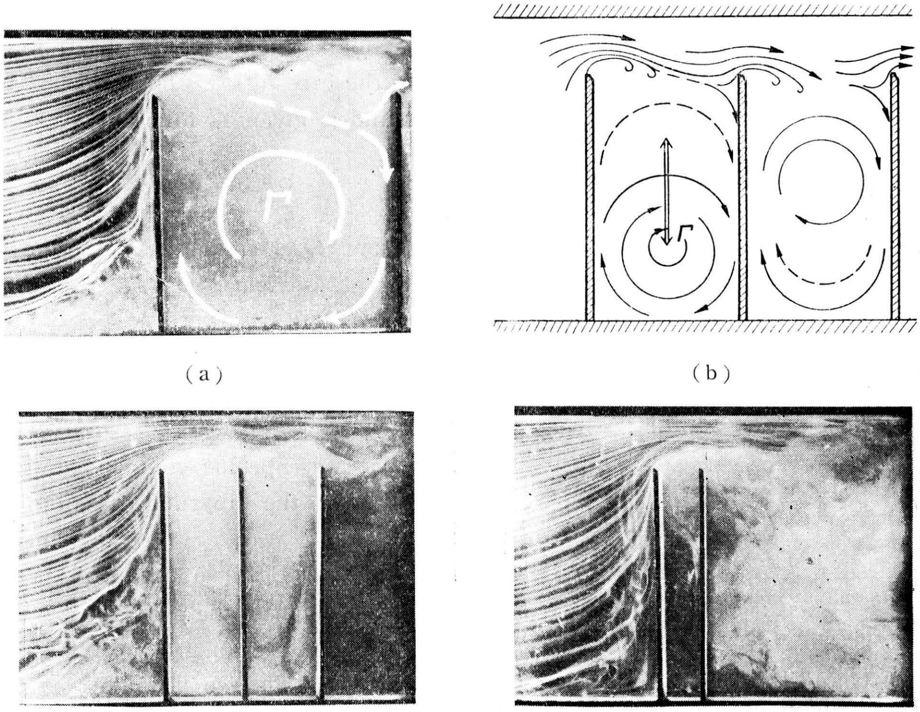
Dimensions of the models used in this experiment are as follows, (the symbols are shown in fig. 4-a)

Clearance	$\varepsilon=50$mm
Thickness of the throttling fin	$\delta=5$mm
Pitch of the throttling fins	$l=s+\delta$mm
Depth of the pocket	$h=0\sim30$mm
Distance between successive two throttling fins	$s=40\sim5$mm

These models are made about 100 times as large as the actual size of the labyrinth packing. Flow velocity through the clearance is about 10 m/s, hence the Reynolds nhmber is about 5×10^4. As the smoke discharged from the "comb-type-nozzle" flows with the air, it makes the shape of stripes and it passes to the tunnel. And when it flows through the model, it can be observed through the glass window, and also it is possible to photograph the flow patterns.

III Flow Patterns

(1) **Flow Patterns in the Rectangular Pocket** Fig. 2-a illustrates the flow pattern in the pocket of the labyrinth packing of straight-through type the sections of which is square with proportion for practical use. When fluid flows into the pocket through the clearance, the flow area is contracted, and after the minimum section, the flow begins to diverge with an angle θ. One part of this stream impinges on the second throttling fin, and is split off from the main flow and deflected downwards. Then a vortex Γ rotating slowly and steadily towards the right is produced in the pocket. The other part of the diverged flow runs into the next clearance without any energy dissipation. This is the so called "carry-over". The energy subtracted from the main flow would be partly transformed into heat in the mixing process i. e. process to feed the kinetic energy to the vortex in the pocket. By friction with the wall of the pocket and by the internal friction



(a) (b)

(c) (d)

Fig. 2 Flow Patterns in the Rectangular Pockets

of the vortex, its rotating energy would be transformed into the heat, and dissipate to the surroundings.

The above-mentioned flow pattern is the most common and standard shape, and in the deeper or in the shallower pocket, the rotating motion of the vortex becomes slightly unstable and the core of the vortex Γ begines to oscillate up and down or to right and left. These states are shown in fig. 2-b, and fig. 4-a. In these states no change is observed in the main flow, and the diverging angle θ is also a constant, about $5^\circ \sim 6^\circ$.

Let us consider the case in which the pitch is smaller. At $h/s>2$ (fig. 2-c), where h is the depth of the pocket and s is the distance between the successive two throttling fins as shown in fig. 4-a. the fluctuation of the vortex core in the pocket becomes quieter, and the bottom part of the pocket becomes so to speak "dead space". At $h/s>5$ (fig. 2-d), the fluid flows over the two clearances the same as flowing over only one throttling, i. e. the fluid does not flow into the pocket, and all the fluid is *carried over.* As mentioned above, as the pitch of the throttling fins becomes smaller, the "carry-over" becomes larger, and consequently the leakage loss increases.

(2) Flow Patterns in the Shallower Pocket In my previous papers, it has been experimentally ascertained that the smallest leakage loss was obtained with the shallow rectangular grooves. One of these results is shown in fig. 3; ϕ is a function which indicates the leakage loss and is given as follows.

$$\phi = G/F\sqrt{g\frac{P}{v}} \qquad (1)$$

where G= Leakage loss (measured) kg/s
F= Clearance area m^2
P= Static pressure before the labyrinth packing kg/m^2 abs.
v= Specific volume before the labyrinth packing m^3/kg

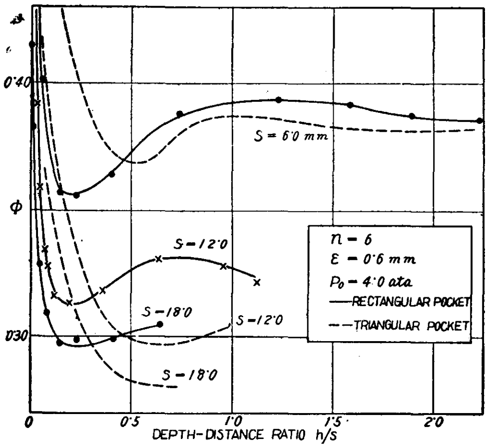


Fig. 3 Effect of the Depth of the Pocket

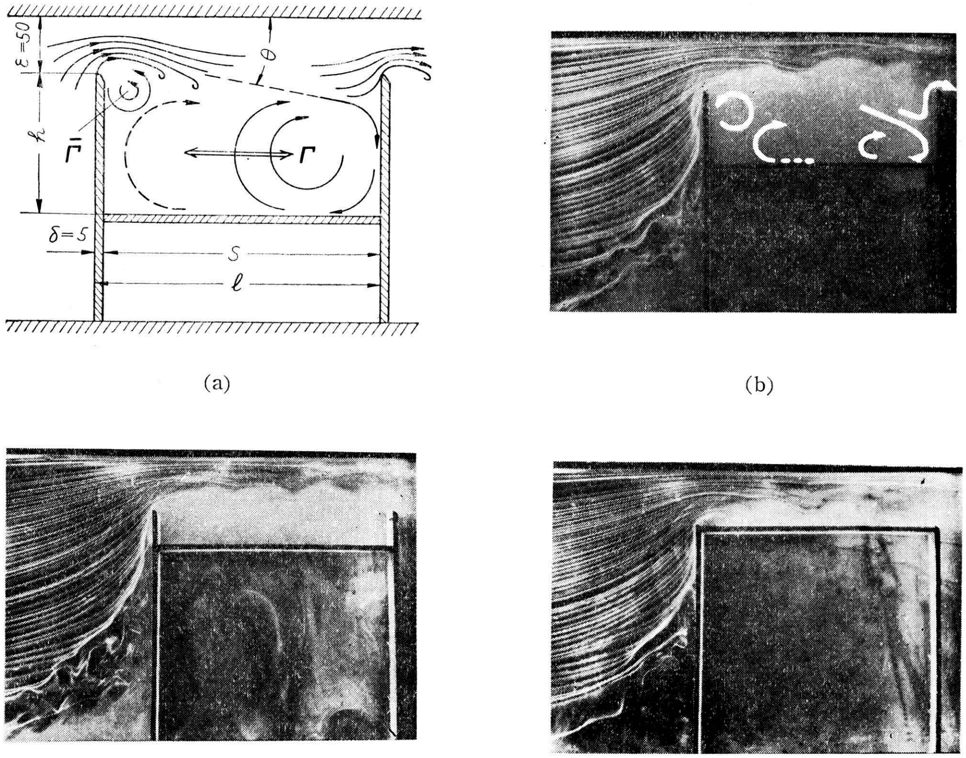
As in fig. 3, the optimum proportion of the shape of the pocket is $h/s \approx 0.25$, at the rectangular groove, and $h/s \approx 0.5$ at the triangular groove. From the relations between the leakage loss and the depth of the pocket, it is supposed that these differences of the leakage loss would be caused by the difference of the flow patterns in the shallower pocket.

The vortex Γ which keeps a balance in the square pocket begins an unstable oscillation to right and left, as the pocket is made shallower. At $h/s \approx 1/2$ (fig. 4-a), it can be seen that a small vortex $\overline{\Gamma}$ rotating reversely is produced at the left corner of the pocket. This vortex would be induced from the the main flow, and it is rotating slowly but unstably. At $h/s \approx 1/4$ (fig. 4-b), —— at this proportion the leakage loss is the smallest ——, the main vortex disappears and the above mentioned reversal vortex becomes rather strong, while no change in the divering angle of the main flow is observed. At $h/s \approx 1/6$ (fig. 4-c), however, the reversal vortex disappears also and the diverging angle decreases and the "carry-over" increases. (*cf.* fig. 3) At $h = o$ (fig. 4-d), the flow path becomes only a smooth channel where there is no throttling, therefor the leakage loss increases much more. From these results of flow observations, the following points should be noticed.

(a) In the square pocket, which is the standard shape, there is a stable vortex in the pocket, and a certain quantity of "carry-over" is seen.

(b) In the deeper or shallower pocket, the vortex becomes slightly unstable but the diverging angle of the main flow is almost constant, so the leakage loss is also constant.

(c) In shallow pocket ($h/s \approx 1/4$), an induced reversal vortex is produced and



(a) (b)

(c) (d)

Fig. 4 Flow Pattens in Shallower Pocket

the main vortex disappears. The presence of such an unstable small vortex would be an advantage; therefor the leakage loss becomes the smallest.

(d) In much shallower pocket, the "carry-over" is on the increase and consequently the leakage loss increases.

(3) **On the Effect of the "Sub-fin"** It is expected that the leakage loss would be reduced when the small "sub-fin" is put in between two main throttling fins. This problem has been studied experimentally[4], and a result is presented in fig. 5. This figure gives the the relation between the leakage loss which is given by the equation (1) and e which is the parameter of the length of the "sub-fin". From this curve, it is obvious that the leakage loss takes slightly small value when the "sub-fin" is small, but it increases considerably when the large "sub-fin" is set.

Let us comsider the relations between these results and the flow visualization study. When a "sub-fin" is in the middle of the pocket, as shown in fig. 6-a, the main stream diverging from the clearance flows into the rear chamber, and a vortex rotating towards the right is produced in this chamber, while a small part is split off from this vortex and flows into the front chamber and a " sub-vortex " rotating towards the left is produced here. In general the main vortex is stable and is rotating quickly but the " sub-vortex " is unstable and is rotating slowly. In this case the leakage loss is reduced a few percent as shown in fig. 5, and this relation is analogous to the case of shallower pocket. But when the larger " sub-fin " is set i. e. at $e/h \approx 1/3 \sim 1/6$, a " blow-up-flow " from the rear chamber hits against the main flow and the main flow becomes unstable; its diverging angle decrases and the " carry-over " increases. These flow patterns are shown in fig. 6-c, d.

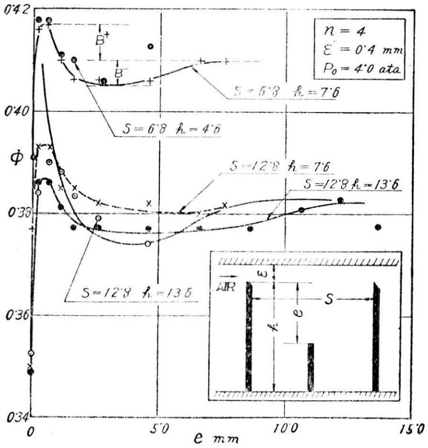
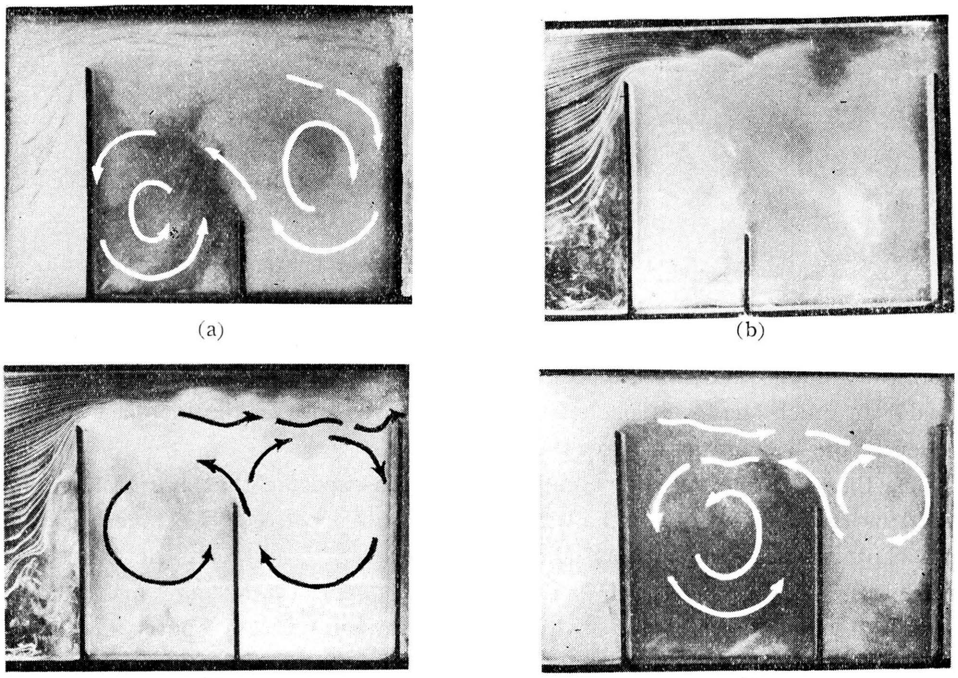


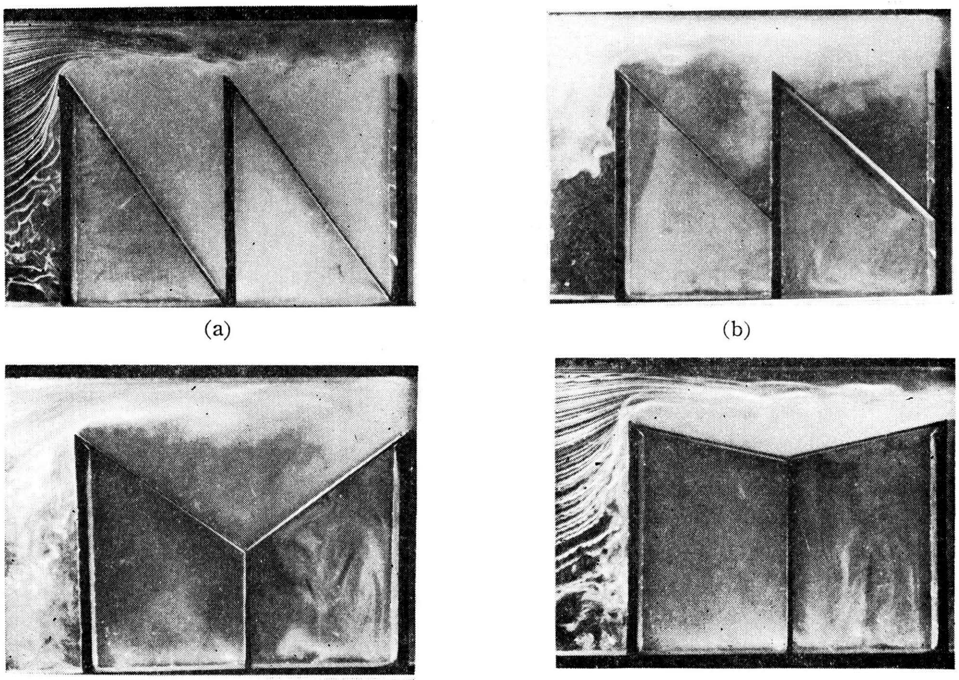
Fig. 5 Effect of the " sub-Fin "



(a) (b) (c) (d)

Fig. 6 Flow Patterns when the „ Sub:Fin " is fitted

(4) **On the Triangular or V-Shaped Pocket** (fig. 7-a, b, c, d). The general flow patterns in the triangular or V-shaped pocket are substantialy identical with those of the rectangular pockets. But in the V-shaped pocket, since the flow



(a) (b) (c) (d)

Fig. 7 Flow Patterns in the Triangular and V-shaped Pocket

impinges on the inclined wall of the second throttling, the contraction of the stream is smaller; then, of course, the leakage loss should increase.

(5) **On the Staggered Type** Concerning the leakage loss through the staggered type labyrinth packing, which has not been studied by us, from the works by Egli[6] and others, it has been learned that the leakage loss was smaller than that of the straight-through type because of the decrease of "carry-over". The photographs of these flow patterns are shown in fig. 8-a, b, c, d.

As it may be seen, the stream flowing through the first clearance impinges on the counter throttling fin and is deflected virtically downwards. In this manner a vortex rotating slowly towards the right is produced at the bottom of the pocket. On the other hand, the main stream impinges on the second throttling fin and another rather stronger vortex rotating towards the left is produced behind the counter throttling fin. When the height of the counter throttling fin is $1/3 \cdot h \sim 2/3 \cdot h$, the first vortex becomes more unstable and the second one becomes more stable and stronger.

In view of these flow patterns, it would be obvious that the decrease of the leakage loss is due to the fact that there would be no actual "carry-over". The

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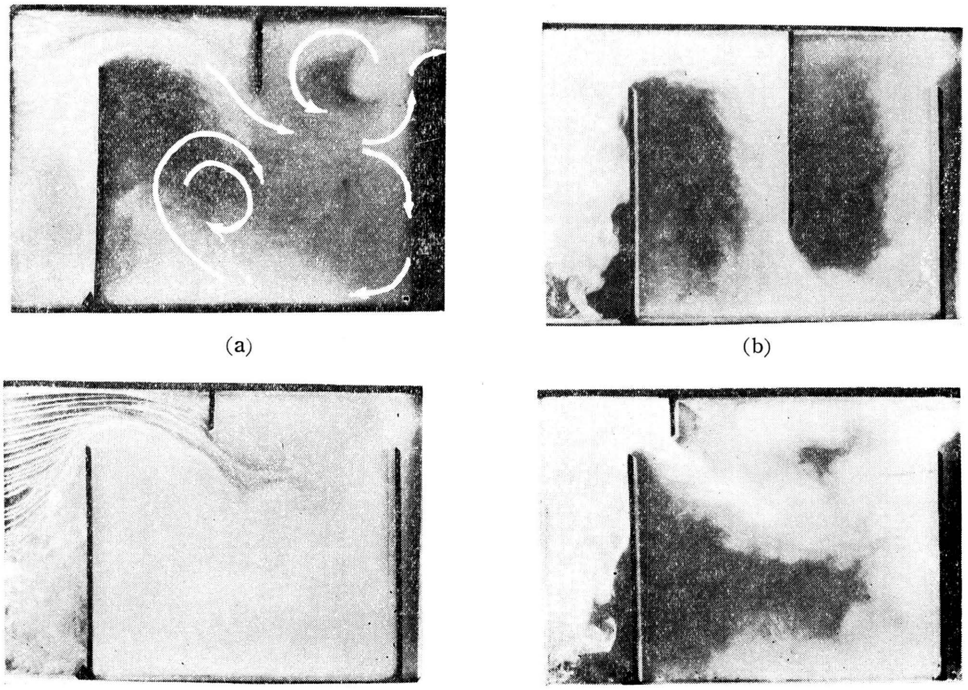
[6] A. Egli, Trans. A. S. M. E. Vol. 57, No. 3, 1935, pp 115/122



(a) (b) (c) (d)

Fig. 8 Flow Patterns in the Staggered Type Pocket

height of the counter throttling fin need not be so large. Even if it is equal to or smaller than the clearance of main throttling fin, "carry-over" is not observed (fig. 8-c, d). Furthermore, this is a great advantage in the construction of the labyrinth packing. Therefor, such a small counter fin may be useful enough.

IV Conclusions

Observing the flow patterns in the pockets of the enlarged model labyrinth packing, and considering the relations between the flow patterns and the leakage loss which was investigated previously, it is concluded as follows.

(1) The most important factor which has an influence on the leakage loss of straight-through type labyrinth packing, is the "carry-over" which depends on the diverging angle of flow from the clearance.

(2) Covering a considerable range of the proportion of the pocket, its angle is little varied.

(3) The situation producing a stabilized vortex in the pocket is not advantageous, but if the main vortex is unstable and a counter rotating vortex is produced —— in the shallow rectangular pocket or when a small "sub-fin" is set between the two throttling fins —— the leakage loss would decrease.

(4) Without doubt the staggered type would have an advantage over other types, but the height of the counter throttling fins need not be so large, and small counter fins would be effective enough.

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