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Influence of compression ratio of foam on printing quality of ink cartridge

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ABSTRACT

The paper had studied the influence of compression ratio of foam on printing quality of ink cartridge. Fundamental properties of foam were first introduced as a review. Thus, some basic models for compression of foam could have been built up to deal with the physical effect of compression on the back pressure of ink cartridge. It might actually make difference on many aspects for an ink-jet printer. By means of experiments, several individual cases had been done which composed of different combinations for the compressed foams and color inks. It turned out that the printing quality might be much influenced in the cases. The results implied that the compression ratio of foam should be correctly chosen in order to yield best quality on the print. Finally, detailed analysis explained to make a suggestion for the choice. It's expected to be very helpful in the future design of ink cartridge with the foam.

Keywords: Foam, Ink cartridge, Printing quality, Ink-jet printer, Porous material

1. INTRODUCTION

Porous material has been successfully applied in the manufacture of ink cartridge since about ten years ago¹. Great progress for the application is still being made so far^{2,3,4}. Compared with other types of ink cartridge^{5,6,7}, the cartridge with porous material (so-called foam at most of time, in general) actually owned some specific advantages, such as high modulation of volume, good liability, low cost, and so on. Generally speaking, the manufacture of ink cartridge having porous material could be simply described in the state flow of Figure 1.0. It's noted that applying some compressive force onto the porous material could modulate the volume with ease. Hence, the compression ratio from one state to another could be achieved with no much difficulty of manufacturing flow.

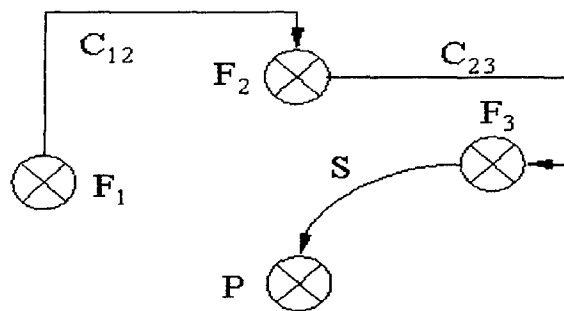


Fig. 1.0: State flow for manufacture of ink cartridge with porous material

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The definition of symbols used in Figure 1.0 was also given on the Table 1.0. First of all, the raw foam F_1 at original state could be compressed to a felted state of F_2 by so-called felting method. The compression ratio would be defined as C_{12} . Secondly, the foam F_2 would be loaded into a cartridge with compression ratio of C_{23} . Meanwhile, applicable ink would be filled into the foam F_3 where the ink could be stored in the pores due to the capillary force. This capillary force was actually acting as a negative pressure to balance the gravity of ink in nature.

Foam's state :	$\begin{cases} F_1 \equiv \text{at original state} \\ F_2 \equiv \text{at felted state} \\ F_3 \equiv \text{at cartridge state} \end{cases}$
Compression ratio :	$\begin{cases} C_{12} \equiv \text{Compress } F_1 \text{ to } F_2 \\ C_{23} \equiv \text{Compress } F_2 \text{ to } F_3 \end{cases}$
Stored with ink :	$S \equiv \text{Surface tension of ink}$
Pressure state :	$P \equiv \text{Pressure in cartridge}$

Table. 1.0: Definition of symbols in the state flow

It's significantly noted here that the equilibrium of force could be expressed in the equation (1.a) where A was area of action, ρ was liquid density, g was acceleration of gravity, h was liquid height, L was length of action, γ was surface tension of liquid. The value of h could be exactly solved if a circular model of action with radii of r was assumed, as shown in equation (1.b).

$$A \times \rho g h|_{\text{gravity}} = L \times \gamma|_{\text{capillary-force}}, \quad (1.a)$$

$$h = \frac{2\pi \times \gamma}{\rho g r} \quad \text{if } A = \pi r^2, L = 2\pi r, \quad (1.b)$$

Furthermore, two fundamental conditions should be at least satisfied in the ink cartridge. One was that the ink stored in cartridge could not leak throughout of ink outlet. It's defined as 'no leakage condition'. This condition meant that the capillary force of ink had to be greater than gravity of ink all the time in the foam. Mathematically, it's simply expressed in equation (2.a) where the symbol H , instead of h , represented maximum height of foam in cartridge. The other was that the ink could flow with ease to supply the need of nozzles in the print. No starvation of ink should occur in all print. It's defined as 'no starvation condition'. Mathematically, it could be described as equation (2.b) where the symbol f was introduced to represent the driving force as nozzle firing in the print.

$$A \times \rho g H|_{\text{gravity}} < L \times \gamma|_{\text{capillary-force}} \Leftrightarrow \text{no -leakage condition}, \quad (2.a)$$

$$A \times \rho g H|_{\text{gravity}} + f|_{\text{firing}} > L \times \gamma|_{\text{capillary-force}} \Leftrightarrow \text{no -starvation condition}, \quad (2.b)$$

Additionally, the driving force might be created due to the vibration of PZT for the piezo-type of printhead; in the thermal bubble type of head, it could also be produced by the formation of bubble. Hence, the value of f was depending on what type of head would be applied to the ink cartridge. Experiments could figure it out. It would be further discussed later in next section.

3. COMPRESSION EFFECT

3.1 Model of Compression

One 2-D model of compression was carefully considered as shown in Figure 3.0. Supposed that the porous foam was compressed by external force to change its shape from the initial state (A_1, L_1) to the final state of (A_2, L_2) . Noted that symbols A and L meant the total area and total perimeter of each pore (cell) in the foam. Meanwhile, for example, the four corners were transformed in the indicated paths ①, ②, ③, and ④, respectively. Thus, it's straightforward to define the compression ratio C as the ratio of A_1 to A_2 , i.e. $C = A_1/A_2$. It's important to see here that the total perimeter of each pore might not be changed in compression although the size of pore (cell) became smaller. In fact, we could make a assumption that cellular wall of each pore just got more curved to have no change of perimeter, i.e. $L_1 = L_2$. Hence, by applying the previous equation (1.a), it's predicted that the value of liquid height h would be multiplied by the C times.

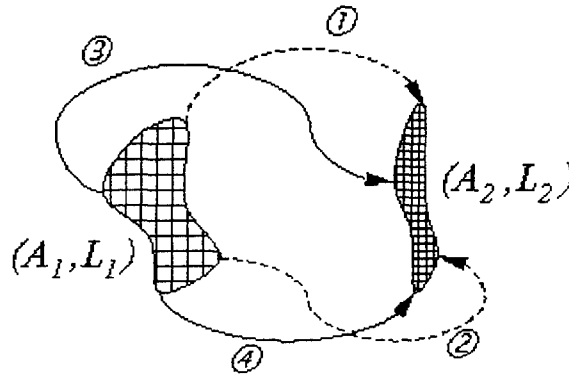


Fig 2.1: Physical model of compression

3.2 Equivalent Principle

It's recalled that more than one time of compression might exist in the foam in the previous Figure 1.0. We'd like to solve such a series of compressions by presenting a simple 'equivalent principle'. The principle was illustrated in Figure 2.2. First, It's assumed that any compression made no difference at all. Therefore, the principle said that the final effect in a series of compressions would be equal to total multiplication of each one. Mathematically, the relationship could be exactly expressed in the equation (3).

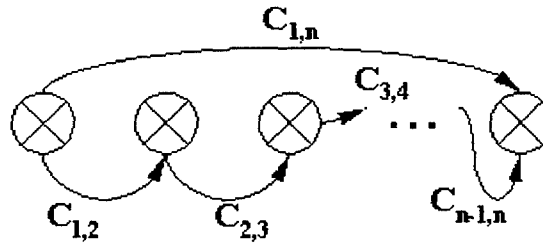


Fig 2.2: Equivalent principle of compression

$$C_{1,n} = C_{1,2} \times C_{2,3} \times C_{3,4} \dots \times C_{n-1,n} = \prod_{i=1}^{n-1} C_{i,i+1}, \quad (3)$$

4. EXPERIMENTS AND RESULTS

4.1 Regular Porous Material

Two different kinds of porous material (foam) were used to see if the 2-D model was working in the previous section 3.1. One kind was taken out from Epson cartridge and the other was from Canon cartridge. The pictures were shown in Figure 3.0. Left and right columns represented Epson and Canon, respectively; in addition, the four rows meant four different foams that were used to store four different colors of cyan, magenta, yellow, and black. In measurement of density, the Epson foams of 0.06 g/cm^3 and Canon foams of 0.13 g/cm^3 were obtained. It most possibly meant that the compression ratio C_{12} of Epson was greater than Canon's one. Thus, it was showing in the pictures that the Canon cells were curved more complicatedly than Epson ones. In fact, the foams in right column had greater capillary height than the left column did. Hence, the results could be a part of proof for the 2-D model.

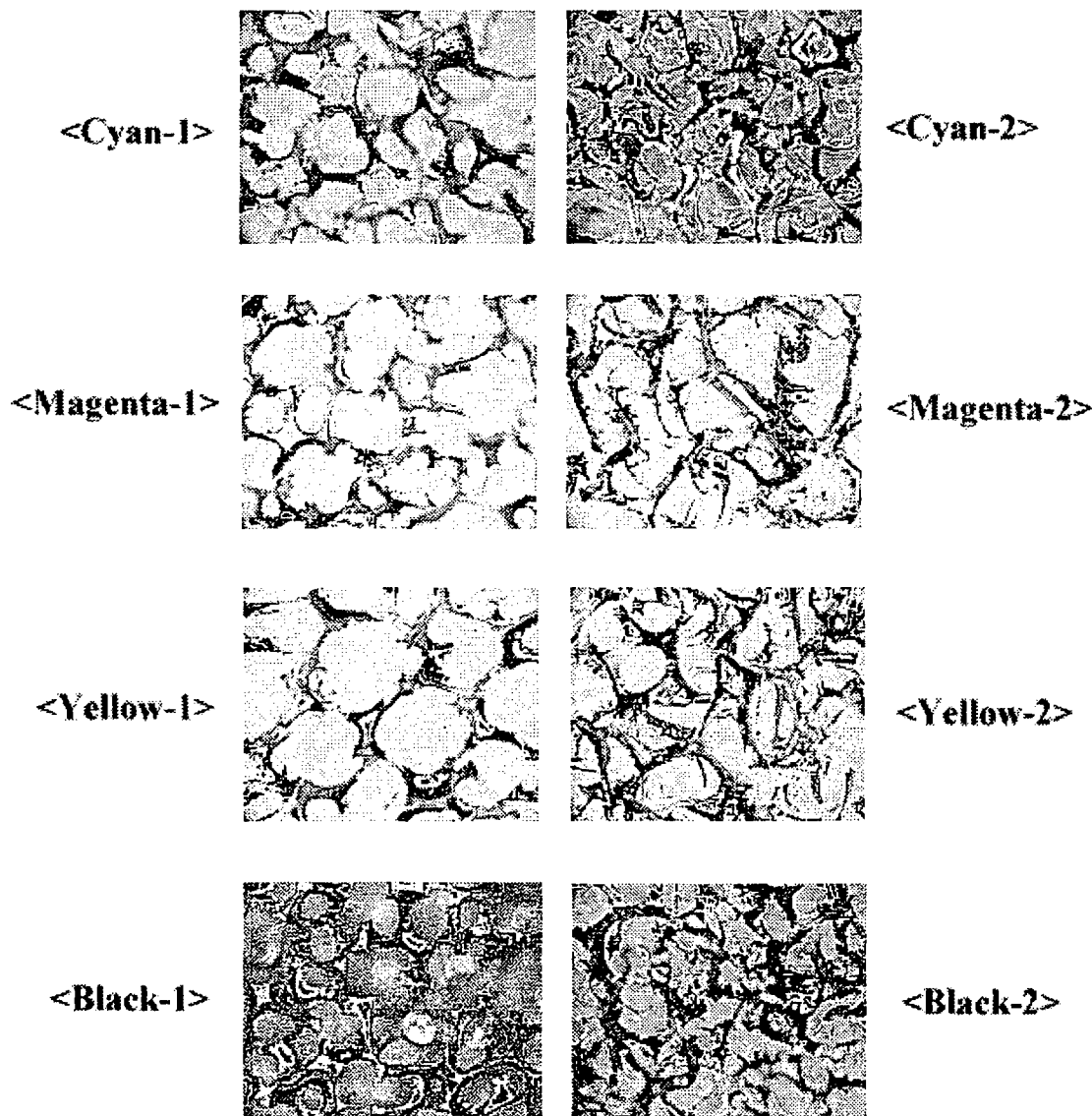


Fig 3.0: Pictures for two kinds of porous material

4.2 Linear Relation of Compression

Experiments were also done to see whether the relationship of compression effect was linear in 2D-model. First of all, four kinds of foam with different compression ratio C_{12} were prepared in the test, along with four different colors of inks. Noted that each piece of foam was $10.1\text{mm} \times 16.0\text{mm} \times 45.7\text{mm}$ where the height H was 45.7mm and the area A was $10.1\text{mm} \times 16.0\text{mm} = 16\text{ cm}^2$. However, in order to satisfy the need of capillary height, four pieces of foams were stacked upward together yielding total height of around 18.3 cm . Next, the initial weight W_i (g) for each foam was measured as shown at the part <a> of Table 2.0. For convenience, all foams were storing with full level 45.7cm of ink first and then put into a closed container for observation. It's obviously found that the ink level would automatically drop downward soon to its equilibrium state as described in equation (1.a). Total 47 hours were taken to make sure its stability of state. In the mean time, the final weight W_f (g) of each foam was measured then as shown at the part of Table 2.0. Secondly, the void ratio V.R. of foam, defined as equation (4.a), was calculated as shown at the part <c> of Table 2.0. Finally, the equivalent height of capillary action could be figured out by applying the equation (4.b). The computational results of height (cm) were shown at the part <d> of Table 2.0.

$$V.R. = \frac{W_f - W_i}{V} \quad (4.a)$$

$$h_{\text{capillary-action}} = \frac{W_f - W_i}{A \times V.R.} \quad (4.b)$$

<a>									
C_{12}	Yellow	Magenta	Cyan	Black	C_{12}	Yellow	Magenta	Cyan	Black
3	3.09	2.59	2.70	2.69	3	17.14	13.81	13.12	16.00
4	3.36	3.31	3.59	3.39	4	17.28	17.06	18.13	22.26
5	4.09	4.29	4.02	4.14	5	20.69	21.23	19.82	22.05
6	4.61	4.63	4.60	4.86	6	24.57	25.14	23.76	25.48

<c>				
C_{12}	W_i (g)	W_f (g)	V_i (cm^3)	V.R. (%)
3	0.56	7.56	7.38	95
4	0.74	7.87	7.38	96
5	0.97	8.02	7.38	95
6	1.10	7.85	7.38	92

<d>				
C_{12}	Yellow	Magenta	Cyan	Black
3	9.15	7.30	6.79	8.67
4	8.97	8.86	9.37	12.16
5	10.81	11.03	10.30	11.67
6	13.43	13.80	12.89	13.87

Table 2.0: Experimental results of four foams for 2D-linear model, noting that
 <a>initial weight of each foam before the test;
 final weight of each foam after the test;
 <c>computation for void ratio of each foam;
 <d>final capillary height of each foam after the 47-hour test.

Noted that the surface tensions of color ink (yellow, magenta, and cyan) were almost same of 35 dyne/cm; but black ink had a little higher value of 44 dyne/cm. To get rid of experimental error, it's preferred to choose the lowest height as a result in each row of part <d> of Table 2.0. If doing so, it's significantly found that the linear relationship held well on ratio of 3:4:5:6 $\approx$ 6.79: 8.86: 11.03: 12.89. Hence, the results could have met well with the prediction of 2-D model as mentioned in previous section.

4.3 Printing Quality

The experiments for influence of compression ratio of foam on printing quality were done as below. There were two different types of foams (Type A and B) chosen to be loaded into three cartridges (Cartridge A, B, and C). In the foam of Type A, two compression ratio of 2.5 and 2.75 were applied in the printing tests. Thus, total five pages of test pattern were printed. Finally, the results of printing quality was shown in the Table 3.1. Meanwhile, the foam Type B with two compression ratio of 2.5 and 3.0 were applied in the next printing tests, too. Once again, total five pages of test pattern were printed. Consequently, the results of printing quality was shown in the Table 3.2.

Cartridge A Cartridge B Cartridge C				
Foam Type A	Compression	<i>Printing Quality</i>		
	2.5	Excellent	Excellent	Excellent
	2.75	Excellent	Good	Bad

Table 3.1: Experimental results of print quality using foam type A with compression ratios of 2.5 and 2.75

Cartridge A Cartridge B Cartridge C				
Foam Type B	Compression	<i>Printing Quality</i>		
	2.5	Excellent	Excellent	Excellent
	3.0	Excellent	Excellent	Bad

Table 3. 2: Experimental results of print quality using foam type B with compression ratios of 2.5 and 3.0

It's noted that 'excellent' printing quality was defined as no any occurrence of banding lines in the five pages of print. Then, the 'good' printing quality was defined as the result with no more than two pages of banding in the tests. Otherwise, the printing result was defined as 'bad' printing quality in the tests. It seemed obviously that low compression would tend to yield better printing quality in the above test. It would be discussed for details later in the following section.

6. DISCUSSION AND CONCLUSION

6.1 Discussion for Results

The simple 2D-model had been examined with much care to determine two significant aspects of porous material in the study. By taking a lot of clear pictures of some regular foams, their microstructures showed that making more compression might cause more complicatedly curved cells. Since the change of total length for cells might be much less than the change of total area for the cells. Hence, the difference of capillary action could be predicted by the compression ratio of foam.

Secondly, the 'equivalent principle' was presented to further figure out the effects for a series of compressions that could be seen a lot in many ink cartridges. In order to see if it's accuracy, the linear relationship between compression ratio and capillary action should be proven. Some experiments were finished to find that it's approximately linear among the foams with different compression ratios. Noted that some judgements had been made to tell the relation because possible errors should be taken into account. In fact, it's pretty hard to measure the real height of capillary action. Therefore, some equivalent transformation was necessary in the experiments.

Finally, the tests for printing quality were finished. There were two types of foams and three different cartridges in the print tests. It's noted that no leakage must be satisfied in the first place, as shown in equation (2.a). Subsequently, the higher compression seemed to yield worse printing quality in the test cases. This could be explained by applying 'no starvation condition', as shown in equation (2.b). It probably meant that the high capillary force might cause the 'bad' printing quality. Firing force plus gravity for ink should be greater than capillary action so that excellent printing quality could be obtained.

6.2 Conclusion

The influence of compression ratio of foam on printing quality of ink cartridge was studied in the work. As a result, it was found that the compression truly played a significant role in the printing quality. Some key findings could be summarized as below-

- Simple 2D-model: it could successfully predict the effect of compression in advance. Actually, it's found that higher compression would yield more complexly curved cells of foam.
- Equivalent principle: it could be applied to calculate the total effect of a series of compressions. In fact, a linear relation was found among the effects of compressions. Experimental results had met well with the principle.
- No leakage and starvation conditions: the printing quality would be finally influenced by the two conditions. In fact, the conditions should be satisfied in the cartridge with compressed foam inside if excellent quality was desired.

Future work might be proceeding about the quantity of influence on printing quality in some degree. It's believed to be still much of interest in the near future⁸.

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