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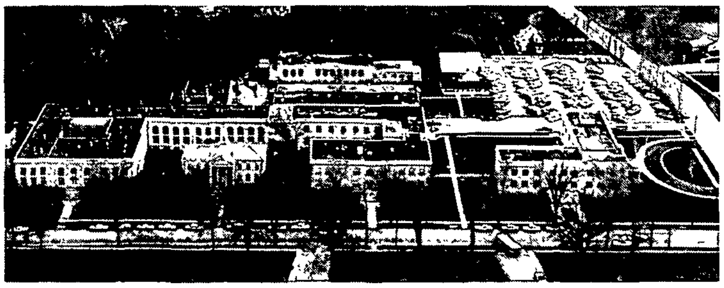

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A MORE FUNDAMENTAL APPROACH TO THE PROBLEM OF HIGH CONSISTENCY FORMING

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ABSTRACT

Many processes in the modern paper mill can be operated at higher consistencies than hitherto possible due to recent advances in the understanding of concentrated fiber suspension rheology (stress vs. rate of deformation behavior). The paper forming process is a conspicuous exception to this general trend toward higher consistencies. Here the fundamental issue is not fiber suspension rheology but rather the microrheology (fiber orientation distribution) of concentrated fiber suspensions during high speed flows. To investigate higher consistency forming from a more fundamental perspective, several techniques are considered for assessing fiber orientation in the bulk of such systems. It is shown that high resolution flash x-ray techniques can be employed to image 25 μm tracer fibers in concentrated suspensions flowing at velocities on the order of 10 m/s. Plans to employ this technique to investigate fiber orientation in several well controlled flows are discussed.

INTRODUCTION

Tremendous progress has been made in the area of medium consistency (MC) processing during the last two decades. One method by which to emphasize this and simultaneously identify those areas where effort is still required is to compare the "typical" mill operation of twenty five years ago with that of a modern installation employing MC processes. The state-of-the-art circa 1961 can be assessed from several texts which appeared at approximately that time (1,2,3). Figure 1 shows the range of typical water distributions (kg water/kg fiber) for various mill processes at that time.

Pulp leaving the blow tank at approximately 10% consistency was diluted prior to bleaching. Common bleaching stages at the time included chlorine, alkali extraction, chlorine dioxide, peroxide and hypochlorite. Typical operating consistencies are listed in Table 1.

Table 1 Typical 1961 bleaching conditions

Bleaching Stage	% Consistency
Cl	3-4
E	10-18
D	10-15
P	5-20
H	10-15

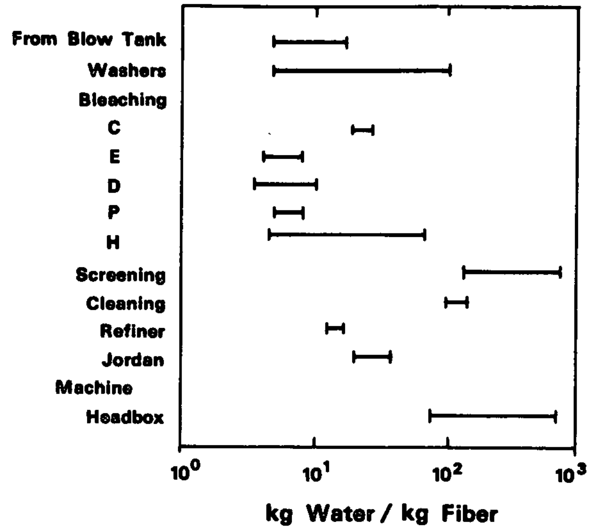

Fig. 1 Water distribution in typical processes circa 1961.

Rotary vacuum filter systems were employed for pulp washing. Consistencies varied widely during these operations with vat and final sheet consistencies ranging between 1.0-1.3% and 14-16%, respectively. Dilution factors ranged from 3.0-6.0 depending on performance.

Screening and cleaning were carried out at extremely high dilutions. Rotary devices employed for fine screening operated in the 0.1-0.6% consistency range, while centrifugal cleaners performed best in the 0.5-0.75% range. While discussing high consistency and pressure screens in 1962, Schaffrath (4) mentioned that "The economies of screening and pulp thickening have stimulated considerable research work in the field of high consistency screens. Consistencies in the range of 1.5%, as opposed to 0.1 to 0.6% found in conventional screening systems...." Pressure screens were just beginning to make "high consistency" screening technically feasible at that time.

As is true today, refining operations were among the higher consistency process steps in 1961. Disk refiners operated at 5.0-6.0% while jordans typically performed in the 2.0-4.0% range.

The 1961 Fourdrinier machine operated at much lower speeds than today but was not significantly different in terms of operating consistencies. Headboxes received stock at 0.1-1.0% consistency, depending on grade. Paper webs reached press sections and dryers at approximately 20 and 40%, repectively.

MEDIUM CONSISTENCY DEVELOPMENTS

Pulp Storage and Transport

Trends in continuous pulping plus the ever-increasing importance of mechanically processed recycled fiber have increased the range of consistencies at which fiber lines may begin. Any potential advantages from less process water at this point would be lost without developments in MC storage, discharging and pumping. Gullichsen and coworkers

(5,6) discussed the principles involved in these MC processes and described commercial operations in the 10-14% consistency range in 1981.

"Fluidization" of Concentrated Suspensions

The basic operating principles for several MC processes can be traced to the fundamental concept of concentrated suspension "fluidization" developed by Gullichsen (7) and illustrated in Fig. 2. When at rest or when subjected to slow deformation, concentrated fiber suspensions exist as coherent networks which exhibit considerable strength. At sufficiently high shear rates the network can be disrupted and the entire suspension becomes turbulent. The rheological (stress vs. rate of deformation) properties of such a turbulent suspension become very similar to those of pure water and allow for confident design of higher consistency devices.

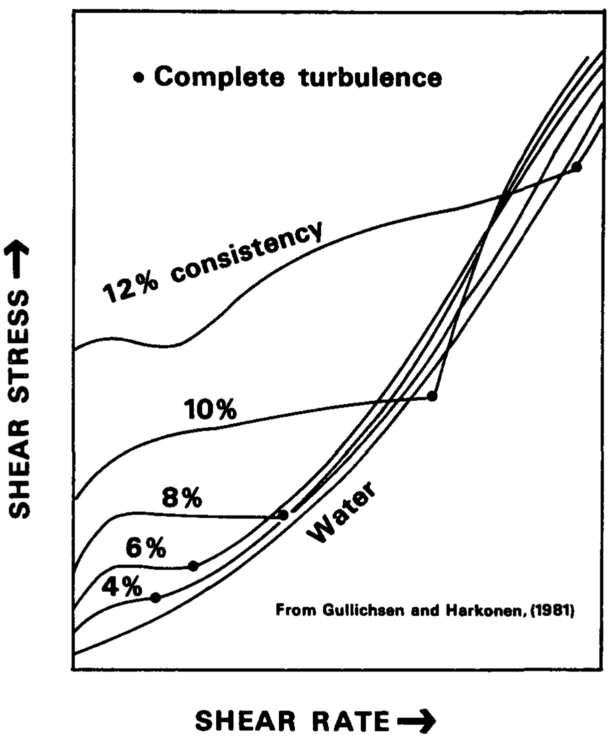

Fig. 2 Concentrated fiber suspension "fluidization" (7).

This behavior closely parallels two other phenomena known to exist in turbulent flows. Polymeric drag reducing agents increase zero shear rate viscosity slightly but significantly lower effective solution viscosity in the turbulent regime. The second parallel is the effect of fluid viscosity in turbulent flow of homogeneous fluids. Shear rates required to produce turbulence increase with viscosity. However, once this regime has been reached the turbulent structure is essentially independent of viscosity.

Bleach Plant Operations

Several developments have worked synergistically to make the operation of all bleaching processes in the medium consistency range possible. Among these are displacement bleaching, oxygen bleaching, and medium consistency chlorination.

The first laboratory investigations of displacement bleaching were those of Rapson and Andersson (8) in 1966. Pilot scale feasibility was shown by Gullichsen (9) in 1973. At that time, wide commercial use was limited mainly by process equipment materials requirements. In 1979 Gullichsen (10) summarized the history of displacement bleaching to that point, including the first commercial installation in 1975.

The first few displacement bleaching installations involved conventional chlorination steps. By 1979 the "fluidization" concept had been applied to the problem of mixing chemicals (both gaseous and liquid) with MC pulps. This allowed the chlorination step to be accomplished at higher consistencies than before. Gullichsen (10) documents the first commercial MC chlorination-displacement bleaching operation. Displacement bleaching installations since 1979 have generally incorporated MC chlorination, since it allows the entire bleaching operation to occur within one tower at 10-12% consistency.

Environmental and safety concerns have led to the development and broad use of oxygen bleaching. This technology has been applied in two forms. One is as an extended delignification step prior to final bleaching, while the other is as an aid to the caustic extraction stage. Oxygen bleaching often replaces (traditionally low consistency) chlorination. McDonough (11) points out that oxygen delignification can now be carried out at low, medium or high consistencies. Higher consistencies employ smaller reactors, while greater dilution allows the oxygen to totally dissolve. Most systems now operate in the 25-30% range.

Pulp Washing

Medium consistencies have been used in the washing area for some time. Pressure diffusers and belt washers use the same principles of operation as displacement bleaching. Liquid is displaced in cross-current fashion through a thick moving fiber mat. Consistencies remain in the 8-14% range throughout the washing process.

Screening and Cleaning

Screening inlet consistencies have increased steadily from the late 1960's and appear poised to increase very significantly in the near future. In 1968, Racine (12) described a "high consistency" pressurized screening installation operating in the 1.0% range. Henshaw (13) described a liner stock screening system operating at 3.5% in 1975. Relatively fine screens were operated at 2.0%, while coarser ones could perform up to 5.0%. A 4.0% waste paper screening and cleaning operation was described in 1982 (14).

Recently, several screening devices have appeared which employ the "fluidization" concept of Gullichsen. By employing very high local shear

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rates the medium consistency stock is made more fluidlike and processible. In 1984 Wedin (15) described a new screen which uses high shear to fluidize, and centrifugal force in the place of foils to clean a stationary screen. This system operated at 3.0% consistency.

Most recently, Gullichsen (16) has documented mill trials of a medium consistency screen operating in the 8-15% range. It also employs his basic fluidization concept.

Lindsay (17) points out that pressure screens designed for operation in the 2.0-5.0% range are becoming common. Systems are available which are based on both inward and outward stock flows. While such consistencies are becoming common, much lower consistencies are still the rule in such applications as tissue and fine papers.

Cleaning is still done at relatively low consistencies with some hydrocyclone systems now being designed for operation in the 1.0-2.0% range (18).

Refining

West (19) made the first systematic comparison between pulps refined at conventional (3.5%) and high (30%) consistency in 1964. He reported that HCR preserved fiber length and improved tear properties. Page (20) observed that fibers refined at high consistency appear to have undergone axial compression. Leach (21) subsequently compared the properties of pulps and handsheets from a variety of furnishes refined at 4.0, 20, and 30% consistency. All pulps responded well to HCR. By the 1970's several patents were issued for HCR plates and devices. Atack (22) studied double disk refining of various wood chips and observed that the optimum operating consistency range was 30-35%. Haas (23) described the operation of a Swedish HCR operation for production of high tear and stretch sack kraft paper in 1970. In this case refiners operated at 32%.

Clearly, refining at higher consistencies has become a well established practice for both wood chip and pulp refining. The exact effects and potential applications of HCR are still being investigated. For example, Nakada (24) has investigated the use of various combinations of conventional and HCR. Duchesne (25) discusses the use of HCR for reject handling.

Medium Consistency Forming

There have been three major activities in this area with the most significant being the FORMFLOW process developed at STFI and subsequently acquired by Ahlstrom Oy. Several papers describe the process (26-30) which was first tested in 1970 by Reiner. Figure 3 shows the general design of this medium consistency headbox. Intense turbulence generated in the explosion chamber serves to disrupt the local floc structure. A more uniform dispersion is produced in the forming and decay sections. In essence, the technique extrudes a single continuous floc.

Figure 4 shows one of the demonstrated advantages of higher consistency forming. Pilot studies at STFI showed improved formation in sheets formed at 3.4% as compared to 0.5% consistency. However, the problem encountered in all attempts to form at high consistency was also documented at this time. Table 2 from the same paper compares the physical properties of conventional and medium consistency sheets made at STFI. Out-of-plane strength is improved during medium consistency forming but only at the price of significant losses in in-plane physical properties. This phenomenon is the main reason for the lack of widespread use of this process. The same behavior has been documented during commercial use and is shown in Table 3.

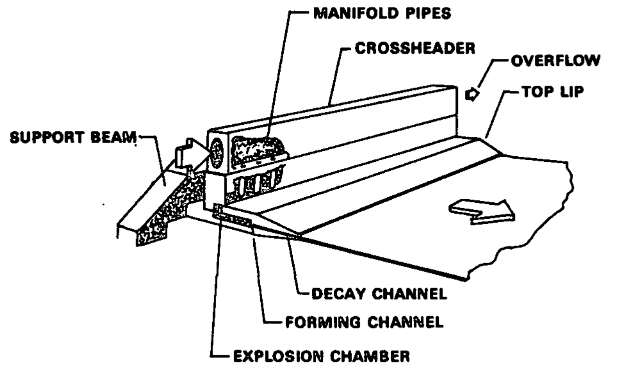

Fig. 3 FORMFLOW medium consistency headbox.

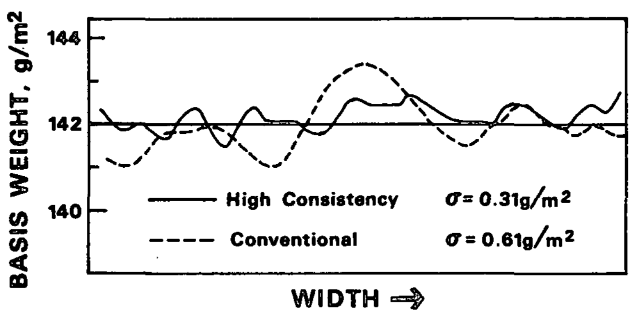

Fig. 4 Formation in MC vs. conventional sheets (27).

The second major contribution to this area was due to Judd and Kranz (31,32). They argued that the increased z-direction orientation present in medium consistency sheets must increase sheet permeability and thus improve moisture transport during pressing and drying. In their final headbox design a small amount of very high velocity water is introduced to promote floc disruption and improve formation. They found that sheet permeability does indeed increase at higher consistency. However, Table 4 again shows the loss of in-plane physical properties.

The final major activity is currently underway in Japan. A five year program was begun in 1982 to produce quality printing and writing grade papers from 3.0% stock. Significant effort has gone into the study of floc stability and devices for floc disruption (33). Medium consistency sheets have been produced on a laboratory former (34). Work is now proceeding to build a pilot machine. A chemi-

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cal dispersing agent was required to give improved formation.

Table 2 Properties of pilot-machine conventional and MC corrugating medium (26)

Property	Conventional	MC
Basis weight (g/m^2)	152	151
Tensile index (kNm/kg)		
MD	60	33
CD	30	26
MD x CD	43	29
Scott internal bond (J/m^2)	200	420

Table 3 Properties of production machine conventional and MC fine paper (26)

Property	Conventional	MC
Basis weight (g/m^2)	122	146
Tensile index (kNm/kg)	37	22

Table 4 Physical properties of conventional (0.5%) and MC (2.5%) sheets (32)

Property	Conventional	MC
Yield strengths (kPa)		
MD	216	85.4
CD	216	43.4
Z	291	204

It is too early to make direct comparisons between medium- and low-consistency sheets produced by this method. However, it is confirmed (35) that the basic problem observed is felted sheet structure. At this time it does appear that the same in-plane physical properties reduction will be observed in this approach.

Several other less widely known works in the area should be mentioned. In 1978 a USSR patent (36) was issued for a medium consistency (3-5%) former. Vibrating rods and plates within the headbox serve to disrupt fiber flocs. Rogut (37) has described the application of medium consistency technology to corrugating medium.

Summary of MC Technology

Figure 5 depicts the current state-of-the-art regarding water distribution in a modern MC operation. While the information is to some degree qualitative and certainly subject to some debate, one conclusion is inescapable. Every operation involved in the manufacture of paper products has made significant progress in reducing associated water volume except the paper forming process itself. While developments in the area of microturbulent headboxes have allowed some small increases in consistency without loss of formation, typical operating consistencies for machine headboxes (especially for high quality papers and tissue) are still in the 0.1-1.0% range.

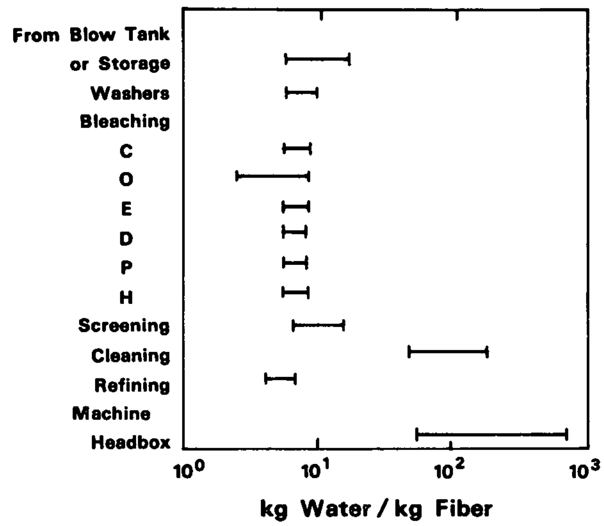

Fig. 5 Water distribution in modern MC processes.

Considering the work now being done by others to solve the remaining problems in MC processes up through screening and cleaning, our efforts are focused on the major missing link in the total MC chain - Medium Consistency Forming.

THE FUNDAMENTAL PROBLEM IN MC FORMING

Physical testing of sheets formed at medium consistency clearly indicates an increased z-direction component in fiber orientation. At medium consistencies this fiber orientation distribution is largely fixed within the headbox. A very simplistic model for what must occur during the forming process at any consistency is shown in Fig. 6. In step 1, fiber flocs which exist at any commercially viable consistency must be disrupted to form a deflocced three dimensional suspension (fluidized). To achieve good in-plane physical properties this three dimensional structure must be reduced to a two dimensional system in which the fibers lie essentially in the plane of the sheet (step 2). Microscale turbulence is used to disrupt flocs in conventional operation. At these low concentrations, fibers are allowed to form a two dimensional mat during the drainage process. Thus a sheet with good in-plane physical properties is produced, since the fibers are largely coplanar.

This same simple figure allows the cataloging of previous attempts at MC forming and clear definition of the underlying fundamental issues. Step 1 (floc disruption) has been accomplished to date by one of two means. Intense local turbulence is employed in both the FORMFLOW and Judd devices.

Again, these are basically applying the "fluidization" concept of Gullichsen as shown in Fig. 2. The Japanese effort appears to require both intense turbulence and chemical dispersing agents to achieve good formation.

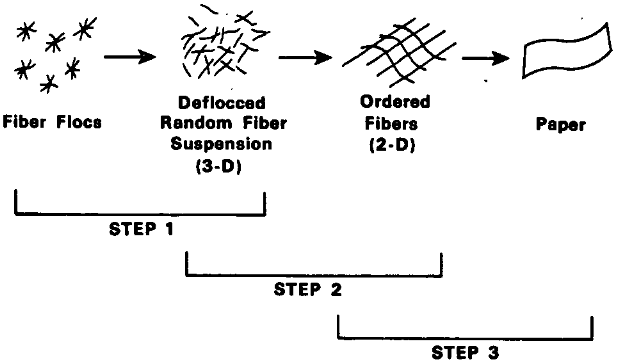

Fig. 6 Conceptual model of forming process.

None of the attempts thus far have achieved step 2 (coplanar fiber arrangement) at medium consistency. Resulting sheets are always three dimensional in nature. The fundamental problem to be overcome if medium consistency forming is to become widely accepted is the lack of control of fiber orientation distribution during the forming process. The problem is not the rheological (stress vs. rate of deformation) behavior of concentrated fiber suspensions (Fig. 2) but rather the microrheology (fiber orientation distribution) of these systems during high speed flows.

FIBER SUSPENSION MICRORHEOLOGY

Fiber suspension microrheology has been thoroughly investigated by Mason and coworkers (38-45) for the case of very dilute suspensions in slow flows. Here photographic techniques are quite adequate for flow visualization. The current area of interest is diametrically opposed to this as shown in Fig. 7. MC forming requires knowledge of suspension microrheology in the high concentration - high Reynolds number regime, where neither theories nor experimental techniques now exist.

The basic problem in studying concentrated fiber suspension microrheology during high speed flows is an obvious experimental one. Photographic techniques cannot be applied, since the suspension is opaque. A first objective of our work in MC forming has been the development of some technique to measure fiber orientation in the bulk of a concentrated fiber suspension during high speed (10 m/s) flow. Several techniques were considered and compared against the most important performance criteria. This comparison is shown in Table 5.

Range of operating consistency must be the top criterion. Type of data acquired is also important. Several techniques give average orientation data. It was felt that, if at all possible, one should directly image fibers in the bulk and build up orientation distribution statistics. If fiber bending is important, direct imaging becomes a necessity.

↑ Increasing Consistency		
	HIGH / LOW* Filled Polymer Processes Mean Field Theories Real Time X-ray (?)	**HIGH / HIGH** M C Processes No Current Theories Flash X-ray
	LOW / LOW Handsheets Noninteracting Particle Theories Photography	**LOW / HIGH** Conventional Papermaking No Current Theories Pulsed Lasers (?)

Increasing Speed ⟶

*Consistency / Speed

Fig. 7 Regimes of fiber suspension microrheology.

Assuming actual fiber images are desired, speed of the experimental technique becomes crucial. Our imaging objective was to clearly visualize a 25 μm fiber traversing the field of view at 10 m/s. This requires exposure times on the order of 100 ns or less. If dynamic data are required, framing rates of 10^3 fps are necessary.

Table 5. Criteria for selection of imaging technique

	% Consistency	Exposure Time (s)	Framing Rate (fps)	Type of Data	Suspension
Light scattering	<1	C	C	A	P
Pulsed laser	<<1	10^{-8}	10^6	D	P
Dielectric properties	>1	C	C	A	T
Birefringence	>>1	C	C	A	M
X-ray	1-100%	10^{-8}	$0-10^4$	D	T
Ideal	0.1-100%	10^{-7}	10^3	D	P

C = continuous measurement
A = average orientation data
D = orientation distribution data
P = paper fiber suspension
T = tracer fibers in pulp suspension
M = model fibers in suspension

Finally, the fiber system to be studied must be considered. At low concentration, photographic techniques can be applied to actual paper fiber suspensions. Some techniques may work with model systems in which all paper fibers are replaced with model fibers which give some measure of orientation. Intermediate between these extremes are possible tracer techniques. An imaging technique in which paper fibers and water appear transparent could be applied if a suitable tracer can be found. Here "suitable" implies that the tracer can be imaged by the technique of choice but is equivalent to the paper fibers in all other important aspects.

No perfect imaging systems seems to exist. It appears that some high speed x-ray system employing

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appropriate tracer fibers offers the best chance for success.

FLASH X-RAY RADIOGRAPHY

A number of x-ray cineradiography, flash radiography and flash cineradiography systems can be found in the literature (46-49). Several of the more important devices are listed in Table 6. Depth of penetration and resolution are always among the key questions here. As energy increases, penetration increases but resolution deteriorates due to scattering as shown in Fig. 8. Resolution is primarily a function of x-ray spot size and geometry as shown in Fig. 9. Note that speed (exposure time) is not a factor with any of the flash systems as pulse durations are typically 30 ns. Resolution of several of these devices has been tested using fine tungsten filaments. The LLL machine can clearly image 12 μm filaments and probably even finer with further work. 25 μm filaments were clearly seen with the H-P system, while the LANL(SP) device could resolve 100 μm wires.

Table 6. X-ray imaging systems

Builder	Exposure Time (s)	Framing Rate (fps)	X-ray Spot Size (mm)	Energy (KEV)	Resolution[a] (microns)
LANL (sp)	10^{-4}	10^{4}	3.0	150	100
Realtime	10^{-2}	10^{2}	<1.0	100	25
LLL	3×10^{-8}	0	0.02	150	5
H-P	3×10^{-8}	10	2.0	300	25
Impulse-physics	10^{-7}	10^{3}	1.0	150	50

[a]Anticipated resolution in some cases.

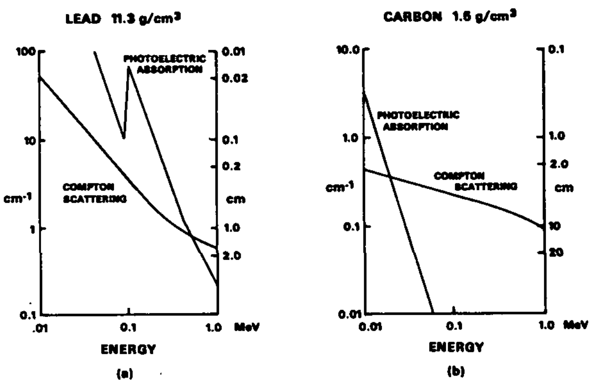

Fig. 8 X-ray scattering and absorption.

A simple flow loop was constructed to assess the ability of the H-P system to visualize 25 μm tungsten filaments within a concentrated suspension flowing at 10 m/s. The portable flow loop shown in Fig. 10 was shipped to the H-P laboratories at McMinnville, Oregon for testing. As the device had to be portable, large MC pumps were not feasible. A 2% suspension of hardwood fibers which could be easily pumped was used for these tests. This is appropriate, since our sole objective was to test the system's imaging capability. A simple converging duct flow channel was used in the imaging zone and is shown in Fig. 11. The entire setup is shown in Fig. 12.

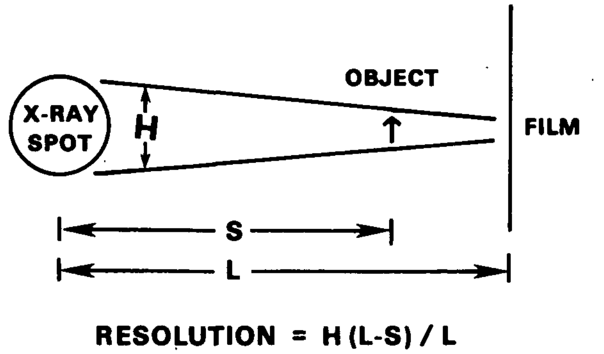

Fig. 9 X-ray system resolution.

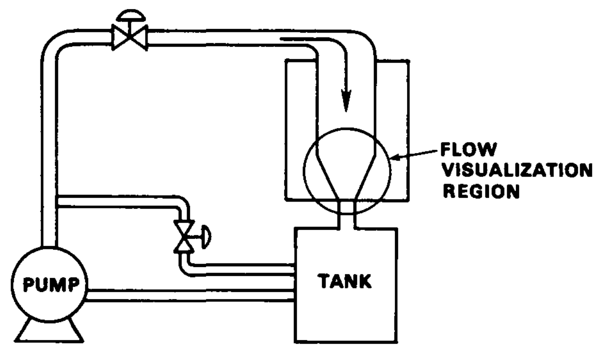

Fig. 10 Portable flow hoop.

Fig. 11 Converging duct section.

Results of these preliminary tests were quite encouraging. Both 50 and 25 μm diameter tungsten wire were clearly imaged in the flow chamber at exit velocities on the order of 10 m/s. Sample radiographs are shown in Fig. 13-14.

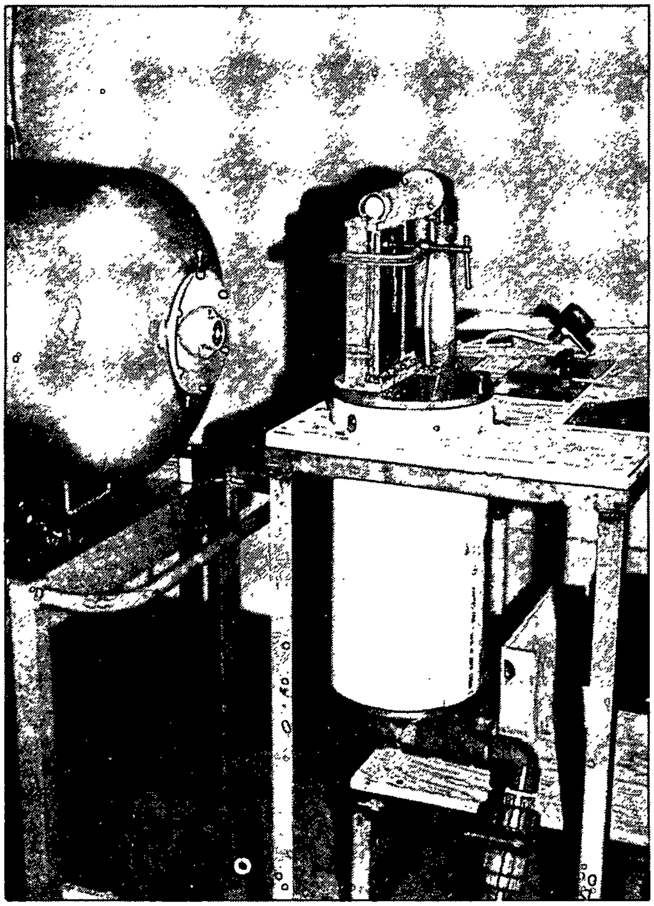

Fig. 12 Experimental setup.

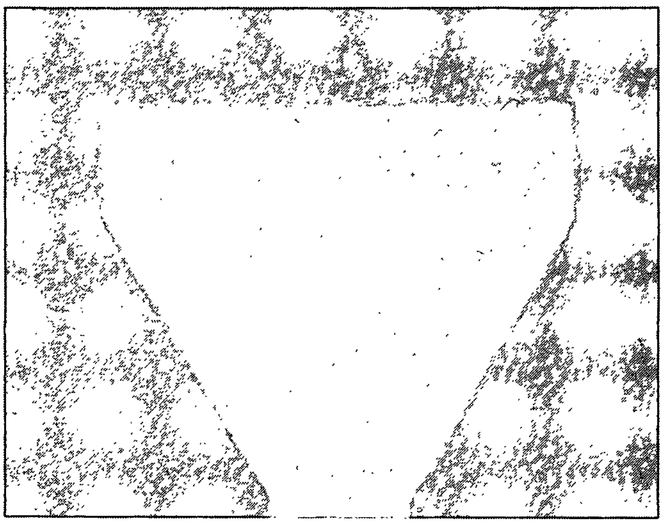

Fig. 13 50 μm Tungsten filaments.

CURRENT STATUS AND FUTURE WORK

High resolution flash radiography has been demonstrated to be a potentially powerful technique for the investigation of high speed multiphase flows in general and concentrated fiber suspension flows in particular. Work is just beginning and there are many questions to be resolved before the technique is proven. Some of these are listed in Table 7.

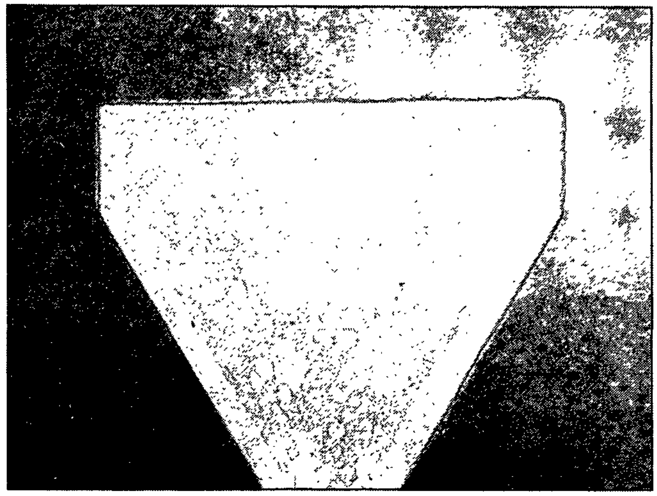

Fig. 14 25 μm Tungsten filaments.

Table 7 Issues regarding x-ray/tracer fiber approach

X-ray system	
	Exposure time
	Resolution
	Penetration
	Speed
Tracer fibers	
	X-ray cross section
	Hydrodynamic equivalence (size)
	Mechanical equivalence
	Surface character
	Density

Exposure time is of no concern with the flash devices. Resolution will always be a top priority, although results thus far are very encouraging. Resolution and depth of penetration always trade off to some degree. High framing rates with high resolution seem unlikely (though not impossible) at this time.

Development of a truly appropriate tracer system will be the key to ultimate success of this approach. All tests to date have been with tungsten filaments to enhance and prove imaging capability. Any tracer must be of higher x-ray cross-section relative to the pulp suspension. Tracer fibers must be of the same dimensions as the bulk fibers. Of the parameters to consider, mechanical equivalence (stiffness) may be the most difficult to achieve. But there are several possible solutions. Surface character of the tracer and bulk fibers must be comparable. The material being imaged in the tracer fibers will always be of greater density than the bulk fibers. This is not of tremendous concern, since the technique will only be applied to concentrated systems where fiber-fiber interactions dominate.

A key point to realize is that these do not form a set of mutually exclusive requirements. For

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example, very high resolution would solve all problems. If 5 μm tungsten wires can be imaged they can be coated to appear as 50 μm paper fibers. While the inner tracer material could be imaged, its presence would have virtually no effect on overall fiber or suspension behavior.

Work to be done in the near future involves more detailed testing of the x-ray techniques to better quantify their capabilities in the crucial areas of resolution and depth of field. More realistic tracer systems will be tested. The technique will then be used to investigate the fiber orientation distributions of concentrated suspensions during certain well controlled high speed flows. This type of information will greatly improve our ability to design and operate MC forming devices.

ACKNOWLEDGMENTS

All x-ray tests done thus far have been performed at either U.S. national laboratories or equipment supplier facilities. The author wishes to particularly acknowledge the substantial efforts by people at Hewlett Packard's McMinnville, Oregon location and at Lawrence Livermore Laboratories. Additional preliminary tests were performed at Los Alamos National Laboratories and at Realtime X-ray Inc., Mountain View, CA. Finally, the author acknowledges the support of the IPC staff and its member companies.

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