Colour-coding schlieren techniques for the optical study of heat and fluid flow

G. S. Settles*

This survey presents a unified view of the history, rationale, applications, and current status of colour-coding schlieren optical techniques, based on an extensive literature review. The characteristics and advantages of this unique flow visualisation tool are discussed in terms of one- and two-dimensional colour-coding, qualitative and quantitative visualisations, and system sensitivity, range and resolution. In particular, the use of matched spatial filters to tailor the schlieren optics for specific applications is stressed. A wide range of past applications in fluid flow and heat transfer is surveyed. Connections are drawn among these applications and some new applications are discussed.

Keywords: *flow visualisation, compressible flow, convection, schlieren optics, modelling*

Schlieren techniques are basic and valuable tools in a range of scientific and engineering disciplines; they allow otherwise invisible light refractions (phase differences) in transparent media to be seen and recorded. Many words have been written on this subject over the years, and some excellent general reviews are available[1–15]. However, the specific addition of colour to the schlieren image, its history, and its rationale of application have been somewhat confused in the literature. This survey provides a unified view of the available colour-coding schlieren techniques and their applications, based in part on an extensive literature review.

The justification for colour in schlieren images has been a subject of past debate. Some have argued that it serves little real purpose other than showmanship, while others have claimed that it always has a definite technical utility; the truth appears to be between these views. Colour serves the same purpose here as in computer graphics, microscopy, satellite imagery, and many other scientific tools: it provides an extra dimension, where required, for coding the features and enhancing the contrast of displayed information.

There are several advantages to be gained from adding colour to the conventional monochrome schlieren image. Colour *coding* is useful in investigations where additional data, such as gradient magnitudes and directions, are required. Colour *contrast* is similarly useful in distinguishing the features of the schlieren field from one another and from the silhouettes of opaque objects. The advantage of the perceived contrast of a colour scale[17] versus that of a grey scale gives the effect of added sensitivity if it is not offset by the sensitivity loss inherent in some colour schlieren techniques. In some cases the hue, saturation, and intensity of the colours are useful as aids in the quantitative analysis of schlieren images. The colours also make it easier to refer to particular features of the image, and they sometimes help reconcile the conflicting requirements of high sensitivity and a broad measuring range. A colour schlieren image is more evenly illuminated than a black-and-white image. Finally, colour schlieren images often have an aesthetic value in addition to their technical value, making them useful for teaching, demonstration, and a range of possibilities beyond those of a pure diagnostic tool. One must balance these advantages against the disadvantage of added optical complexity, the higher cost of colour image recording and the problems of colour reproduction in publications.

This survey is limited to schlieren techniques in which colour plays an important role and in which real images are produced. The reader is assumed to have a basic familiarity with optics and the principles of schlieren photography, such as could be gained from studying some of the general references cited earlier. A number of related techniques are not covered here, including many which involve phase contrast, interference, diffraction, coherent light, colouring of monochrome images, and non-imaging systems. Since most of the interesting subjects for schlieren observation do not involve significant diffraction spreading, the simplification of a geometric optical treatment is adopted everywhere except in the discussion of image resolution.

Optical principles

A brief account of some optical principles is helpful in understanding colour-coding schlieren techniques. Consider the elementary Toepler[18,19] schlieren system shown in Fig 1. A non-coherent beam of white light from an extended source is collimated by the first field lens, passes through a transparent, refracting schlieren object and is refocused by a second field lens to form an image of the source in the 'cut-off' plane. Here a knife-edge cut-off blocks a portion of the source image. A third lens is then used to focus an inverted image of the schlieren object plane on a viewing screen. Light rays from the extrema of the source are traced through this optical system in Fig 1.

From the optical properties on lenses, one recogn-

* Mechanical Engineering Department, The Pennsylvania State University, University Park, PA 16802, USA

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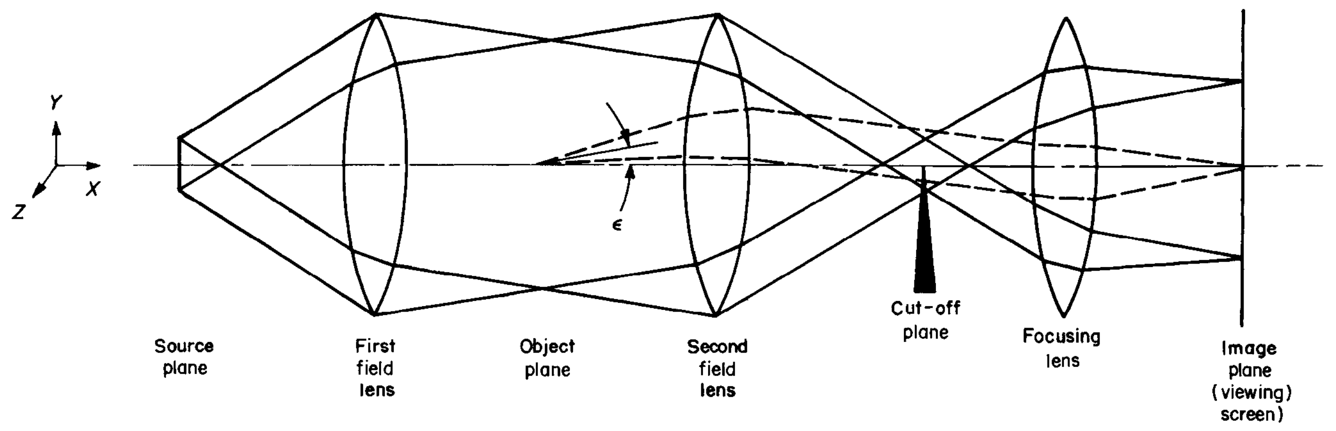

Fig 1 Toepler schlieren system with extended source

ises that the source and cut-off planes, and the object and image planes, are sets of conjugate optical planes bearing reciprocal Fourier transform relationships to one another. Thus each light ray in the object plane is mapped into every point of the source image in the cut-off plane. If no schlieren object is present, then the effect of moving the knife-edge further into the source image is a uniform darkening of the viewing screen. The source image in this case may be thought of as a composite of many weak source images, each one corresponding to a light ray passing through a different point in the object plane.

If a single ray in the object plane is refracted upward and away from its original path by a schlieren object, then a corresponding weak source image will be displaced upward in the cut-off plane (dashed lines in Fig 1). The amount of this refracted light blocked by the knife-edge will thus decrease, and the corresponding point in the schlieren image on the viewing screen will be more brightly illuminated than the background. Similarly, a ray refracted downward by the schlieren object will produce a corresponding dark point on the screen. The conventional black-and-white schlieren image is built up of many such points of varying illumination, corresponding to the shape and strength of the refractive schlieren object.

Note that the specific shape of the light source itself is immaterial to this explanation. Further, the change in image illumination will be initially proportional to the angular refraction, ε, due to the schlieren object. Should ε be so large that the refracted light is moved entirely onto or entirely off the knife-edge, then any larger refraction will no longer cause a change of image illumination; the measuring range of the system will then have been exceeded. Finally, the light refractions in a schlieren object occur due to the refractive index gradient† $\nabla n = (\partial n/\partial y)\mathbf{j} + (\partial n/\partial z)\mathbf{k}$ in the object plane perpendicular to the optical axis. However, only the vertical component of this vector is able to produce changes in light cut-off at the horizontal knife-edge corresponding to changes in illumination of the schlieren image

One may now consider the system of Fig 1 in more general terms as a Fourier optical processor[7,20]. From this perspective, the cut-off plane contains the Fourier spatial frequency spectrum of the light beam, the zeroth order of which is composed of all light not refracted by the schlieren object. Advanced schlieren techniques may be thought of as exercises in devising matched pairs of masks or spatial filters for the source and cut-off planes. The knife-edge, an elementary half-plane bandpass filter, is now discarded in favour of more sophisticated masks chosen to display certain types of information in the schlieren image. In particular, colour schlieren techniques are classified in this review by the way complimentary source and cut-off masks are designed to achieve the desired colour contrast, colour coding, resolution, sensitivity, and measuring range in the schlieren image.

There is a well-known compromise between the sensitivity and the measuring range of the Toepler schlieren system. (At one-half cut-off, these two properties are inversely proportional.) A broad measuring range is desirable for studies of many typical schlieren phenomena containing wide variations of the refractive index gradient. On the other hand, the weakest refractions will no longer be observed if the range is extended at the expense of the sensitivity. As illustrated later in this review, colour-coding is useful in ameliorating this compromise.

The maximum sensitivity of the Toepler schlieren system is limited by light diffraction in the object and cut-off planes. For a single knife-edge cut-off, it has been demonstrated[1] that refractions as small as $\varepsilon \sim 10^{-6}$ rad can be detected before this diffraction limit is reached. This high sensitivity level allows one to observe, for example, temperature gradients of about 1 K°/cm in ambient air.

This sensitivity limit may be compromised, however, by the resolution loss produced by an arbitrary cut-off mask. For example, Rayleigh's criterion dictates that a cut-off slit 0.5 mm wide causes such serious diffraction spreading that schlieren objects of several centimetres cannot be resolved in the resulting image. This effectively limits the choice of useful cut-off masks to those which avoid narrow beam limits. Scattering, distortion, and other defects of the cut-off mask cause a similar degradation of the image resolution. These restrictions do not apply to the source mask, however, since its position in the optical path precedes the schlieren object, where the beam acquires the information needed to produce a highly-resolved image.

Historical perspective

Schlieren techniques are firmly rooted in the history of the optics[21]. Robert Hooke[22] and Christian Huygens[23] both reported schlieren observations in the 17th century, at which time a candle flame had to suffice as both a test subject and a light source. In a classical example of

† n – refractive index; y,z – cartesian coordinates (Fig 1); $\mathbf{j},\mathbf{k}$ – unit vectors in y,z directions

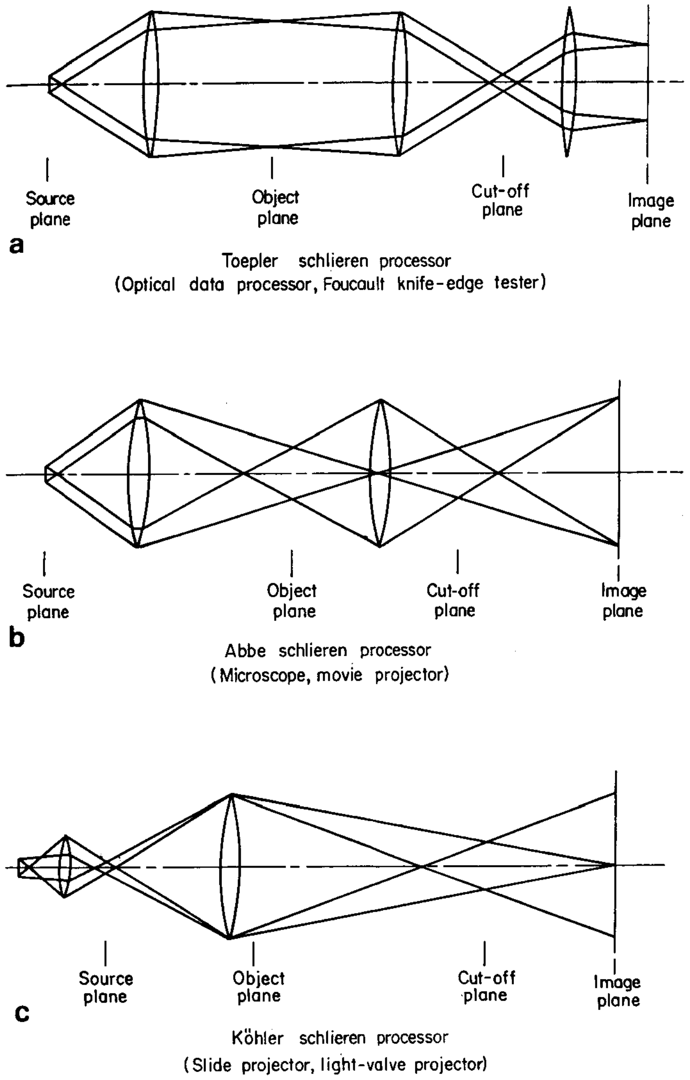

Fig 2 Classification of schlieren-type optical processors

misplaced technology, the technique lay dormant for 200 years. Leon Foucault[24] rediscovered it in the form of his famous knife-edge test for telescopic parabolae in 1859 but it was August Toepler[18,19] who succeeded in developing and popularising the technique for fluid and heat transfer applications, and in giving it a name. ('schlieren' is the German term for striations or inhomogenieties, such as those which occur in poor-quality glass.)

Toepler first observed the schlieren image "sparkling in splendid colours" due to the chromatic abberation of a field lens, which dispersed the source image into a spectrum. He did not proceed, however, to exploit the potential usefulness of this observation. The amateur microscopist Julius Rheinberg[25], in 1896, was apparently the first to do so.

Rheinberg described several colour schlieren techniques for microscopic observations which are still in use today[26]. He correctly identified the advantages of colour contrast over conventional bright- and dark-field microscopy, as well as the colour-coding of the magnitude and direction of refracted and diffracted light: principles which were not recognised in 'conventional' schlieren applications until many years later.

Rheinberg's work was closely tied to that of Ernst Abbe, who had proposed the definitive theory of microscopic image formation[27] in 1873. In fact, Abbe's theory is fundamental to the understanding of the schlieren-type optical processor now used in a wide variety of instruments and devices. Even at the start of the 20th century, such processors were already at work in at least the three divergent fields of microscopy, astronomy, and fluid dynamics. This connection is illustrated in Fig 2, where three basic arrangements of the schlieren processor are shown and some of their applications listed.

The modern pioneer of colour schlieren techniques for fluid dynamics and heat transfer was Hubert Schardin. His comprehensive 1942 paper on schlieren methods and applications[1] is still the best reference on the subject. In it, he described 12 schlieren arrangements of which three produced coloured images: the prism, lattice filter, and colour-background methods.

The post-war development of aeronautics led to the wide usage of colour schlieren techniques for high-speed flow visualisation studies. The prism method of Holder and North[28] and especially the tricolour cut-off filter proposed by North[29] in 1954 were mainly used for this purpose. A connection with the previous work of Rheinberg and Schardin was not recognised by the technical community at the time, and is still overlooked in the literature. Even the widely-known work of Holder and North has been 'reinvented' more than once in the interim.

Useful new colour schlieren arrangements have been proposed in recent years by Cords[30], Maddox[31], Meyer-Arendt[32], and others. Cords' one-dimensional 'dissection' technique is perhaps the most important of these; its advantages were later extended to two-dimensional colour-coding by Settles[33].

Colour schlieren techniques

Most of the available colour schlieren techniques are illustrated and classified in Fig 3 in terms of matched source and cut-off mask pairs added to the Toepler schlieren arrangement.

Most of these techniques involves a colour-band filter in the cut-off plane; Rheinberg's two-colour cut-off filter is the first example[25,34-36]. It produces an image equivalent to the standard black-and-white schlieren, except the grey scale is replaced by a two-colour mixture scale. Some sensitivity is gained from colour contrast, while some is lost to diffraction and scattering at the filter.

The tricolour filter technique due to North[29] has the same characteristics, but a central band is added to give the background a third, contrasting colour. This technique has been very popular[3,4,6,37-61], is easy to interpret, and involves only a trivial modification to an existing schlieren system. These advantages must be weighed against the loss of image resolution when the central band is made narrow for high sensitivity.

Schardin[1] proposed a cut-off mask composed of several colour filter strips arranged in a lattice[8,12,14,52,53,59,62-76], which codes the colours of the image directly to the magnitudes of light refractions in the schlieren object plane. If opaque strips are used to separate the coloured lattice strips, the image then displays 'isochromes' which can be used for a simple quantitative analysis of the schlieren[1,14,31,62,73,74,77,78]. Unfortunately, high sensitivity can only be obtained with narrow lattice strips which destroy the image resolution

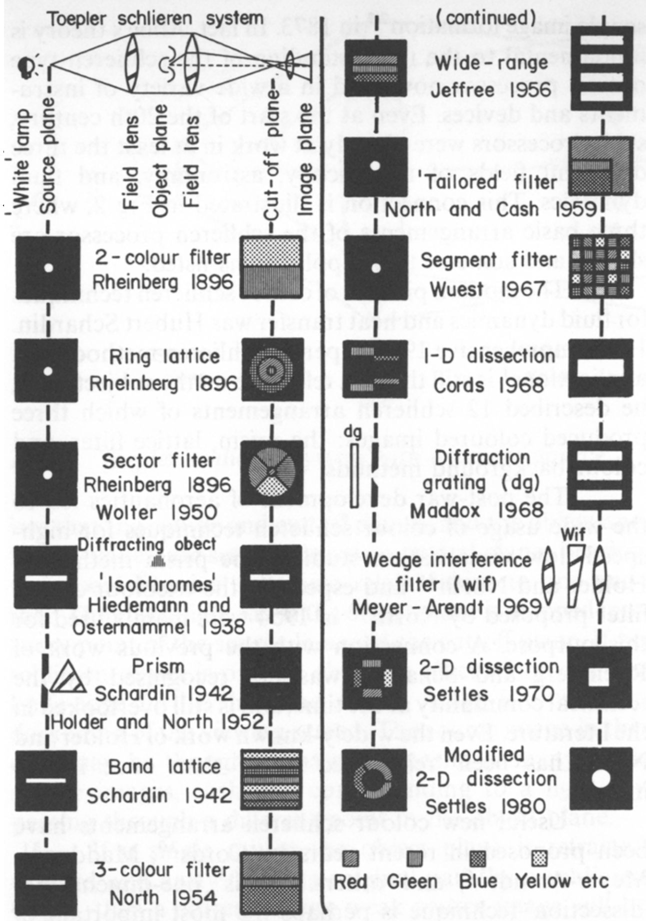

Fig 3 Classification of colour schlieren methods (Reproduced by permission of Hemisphere Publishing Corporation[16]*)*

as discussed earlier. Thus quantitative measurements using the lattice cut-off are practical only if the schlieren gradients are strong.

All the above techniques gain image resolution if the coloured filter is used as a source mask, with an adjustable slit as a cut-off mask. Even so, the slit cannot be made arbitrarily narrow, but it is less disruptive in the cut-off position than a coloured mask[74,79].

The prism[1,3,6,7,9,12-14,28,38,58,59,66,67,73,76,79-92] method due to Schardin[1] and Holder and North[28] uses a prism to spread the light beam into a spectrum, which forms the effective light source of the schlieren system. Part of the spectrum image is then masked by a slit in the cut-off plane. Light refractions in the object plane shift weak images of the spectrum with respect to the slit, causing contrasting colours to appear in the image. This method is thus similar to the lattice filter method described above, and suffers the same restrictions of cut-off slit width and the sensitivity–resolution compromise.

All the techniques described thus far are one-dimensional: they can only display the refraction vector components which are normal to the colour bands. As in black-and-white schlieren methods, two orientations of the matched filter pair may be required to see all the features of a given test object. This restriction does not hold in the two-dimensional colour schlieren techniques described next.

The ring lattice filter[7,8,12-14,72,73,86,87,92-97], first proposed by Rheinberg[25], colour-codes the absolute magnitudes of schlieren refractions without giving any information on their directions. Howes[96] has devised the latest modification of this method, in which the cut-off filter is a colour photographic transparency of a radial spectrum with a clear centre spot. The ring lattice method has possibilities and limitations for quantitative measurement similar to those of the band lattice method described previously.

Rheinberg's sector filter[7,8,14,15,25,98-100] colour-codes the refraction directions but not their magnitudes. To produce a schlieren image with magnitude information as well, Wolter[14,15,100] devised a sector filter with a sufficient number of contrasting colours to code both quantities. In this case the refraction magnitude is keyed to colour saturation and the direction to hue. Wuest[59] suggested a segment filter which codes both quantities explicity by arbitrary coloured segments in the cut-off mask. All these schemes suffer the familiar compromise between sensitivity and image resolution. The segment filter, in particular, is so limited in this respect that it has apparently not found any useful applications to date.

Another compromise of the schlieren instrument, that between the sensitivity and the measuring range, has prompted the development of several wide-range colour schlieren techniques[78,79,101-105]. Jeffree's[79] approach to this problem involves a colour-band source mask and multiple slits in the cut-off plane. The colour cycle is thus repeated several times in the image for strong refractions, effecting an extension of the measuring range without an accompanying decrease in the method's sensitivity to small refractions. Of course, the coding of refraction magnitudes by specific colours is no longer unique in this case. Maddox[6,31,77,106,107] used a diffraction grating to produce a source spectrum and a diffuse, semi-transparent cut-off slit matrix to extend the range while partially alleviating the diffraction effects. Surget[101], Phillips[78], and Rotem *et al*[103-105] also used similar range-extending schemes. Surget[101] mentioned the possibility of using multiple coloured bands in both the source and cut-off masks, thus increasing the overall luminosity and producing a schlieren image of composite colours. The use of extended sources in these wide-range techniques provides the schlieren apparatus with a small depth of focus in the object space, which is usually advantageous.

An important improvement in colour schlieren techniques was proposed by Cords[30] in 1968. His one-dimensional 'dissection' method[38,108] separates the colour bands in the source mask by at least a few millimetres, so a narrow cut-off slit is no longer required to gain high sensitivity. Instead, the sensitivity is controlled by the degree of cut-off of the image of each colour band, while the spacing between the bands (and thus the aperture of the cut-off mask) may be arbitrarily large. By this means the sensitivity and resolution of colour schlieren images were brought into parity with the best black-and-white results for the first time.

Cords' work was extended to a two-dimensional dissection method[6,38,109-120] by Settles[33] in 1970. Here, a square array of colour bands forms the source mask and an adjustable square aperture forms the cut-off mask. The colours in the image are related to the refraction directions by a polar diagram, as in the sector filtering scheme, but the available sensitivity and image resolution are much greater. As shown in Fig 3, a circular arrangement of the colour source bands may be used[16] with an iris diaphragm as a cut-off mask. The benefits of the dissection technique will apply as long as the cut-off mask aperture is at least a few millimetres wide.

Although the above constitute the main colour schlieren schemes, there are other particular schemes which deserve to be mentioned. These include the coloured-background method, in which a test object is observed against a background of coloured bands. Schardin's[1,73,121] version of this technique involves only a standard camera and a coloured backdrop, but its sensitivity is severely limited. Meyer-Arendt[7,32,67,122-124] added a coloured background to a conventional schlieren image by means of a wedge interference filter placed in the optical train ahead of the cut-off plane. This avoids the resolution loss of a cut-off mask, but is limited in sensitivity and is suitable only for visualising strong refractions.

The 'isochromate' method[125-130] of Hiedemann and Osterhammel[125], actually first suggested by Toepler[18], is tailored for strongly diffracting test objects. A standard white light schlieren system with a slit cut-off is used. Diffraction in the schlieren object plane creates spectral dispersion in the cut-off plane which is selectively passed by the slit, leading to a coloured image. This approach also works when the schlieren create spectral dispersion for any reason, as in the case of observations through a stratified water tank[131]. For that matter, the oldest and least useful colour schlieren technique, due to chromatic abberation of the field lenses[18,19,73,132], arises from the same principle. It is generally regarded as a nuisance rather than an advantage, and has been termed 'involuntary colour schlieren' by Weinberg[13].

An important technique on the fringe of the present subject is the schlieren interferometer[3,6,133-140]. A standard schlieren system may be modified by the addition of a birefringent polariscope, usually a Wollaston prism, at or near the cut-off plane. The prism splits the incident light into two slightly divergent, orthogonally polarized beams which interfere in the schlieren image plane. With monochromatic illumination, fringes appear which are shifted in proportion to refractive index gradients in the object plane. However, if the optics are adjusted to the null fringe setting and a white light source is used, then the image appears in the colours of Newton's rings. A good example of the results of this approach is given by Disselhorst and Van Wijngaarden[138].

Finally, as noted by Weinberg[13], few investigators[55,141] have taken advantage of the potential to 'tailor' the matched filters of a colour schlieren system specifically to a certain phenomenon under study. In one such example[141], the cut-off filter was designed to emphasise the features of the high-speed flow over an airfoil which refract light in specific radial directions.

The historical record of matched filter pairs shown in Fig 3 has hardly exhausted the useful possibilities thereof. In particular, the significant recent advances in white light optical processing[20], for example edge enhancement, texture and structure encoding, structure correlation, colour readout of interferograms and holograms[48,142-144], image addition and subtraction, spectrum analysis, etc, have yet to be transferred to the domain of flow visualisation. I believe such a transfer is an important issue for future work.

Colour schlieren applications

The literature survey reveals that colour schlieren techniques have been most useful in the study of complex refractive fields, where either a black-and-white image is confusing or additional information is needed to aid in the image interpretation. This applies, of course, to most of the possible subjects for schlieren investigation, but particularly to cases of strong refractions, refractions over a wide range, highly three-dimensional phenomena, self-luminous or semi-transparent phenomena, and cases where quantitive evaluation is required.

About half the published applications of colour schlieren deal with compressible gas flows. The remainder are divided about evenly among combustion phenomena. convection phenomena, microscopy, glass testing, and a miscellaneous collection of applications ranging from plasma dynamics to colour television projectors.

This section attempts to summarize these applications and to indicate, where possible, the most appropriate techniques and procedures for each application. Specific examples have been drawn from the author's past work. Except for the discussion of recent new applications, a more extensive treatment along similar lines may be found in the classic papers of Schardin[1] and Holder and North[3].

Compressible gas flows

Schlieren optics have long been standard equipment for high-speed wind tunnels, and it appears likely that more has been learned of the behaviour of such flows from schlieren observations than from any other diagnostic method. Many of the references already cited deal with such instrumentation[4,12,29 31,40,59,76,79,82,101,109,112,134,144] without specific details of its application to flows.

High-speed flow visualisation over airfoils[77,83,141,145] has often called for colour-coding to distinguish between shock waves, boundary layer phenomena, and the airfoil itself. Colour schlieren has been used in compressor cascade studies[66,68,98,137] for similar reasons. While the primary need has been for qualitative flow visualisation, quantitative density measurements have also been made successfully. Such measurements seem particularly important in turbomachinery studies, where intrusive probes are difficult to apply and where vibration often precludes the use of interferometry. In one example[45], high-speed colour schlieren films proved important in the study of ejector-type thrust augmentors for gas turbines.

Similar reasons have prompted the use of colour schlieren in compressible separated flows[52,106,146] and shock wave–boundary layer interactions[74,80,116,147]. The distinction among embedded shocks, free shear layers, recirculation bubbles, and the surfaces near which they occur can sometimes be explicitly colour-coded with a proper choice of matched schlieren filters. For two-dimensional flows of significant extent along the optical path, a simple quantitative analysis is often possible.

An example is shown in Plate 1, which depicts the flow from left to right through a Mach 3.9 engine inlet model in a wind tunnel[74]. A shock wave is seen to impinge on the lower surface of the inlet, exceeding the measuring range of the lattice-band colour schlieren method which was used. The boundary layer on the upper surface displays several isochromes characteristic of the refractive index gradients across it. Given the free stream conditions, the widths of the lattice bands, and the parameters of the schlieren system, it was possible to integrate across

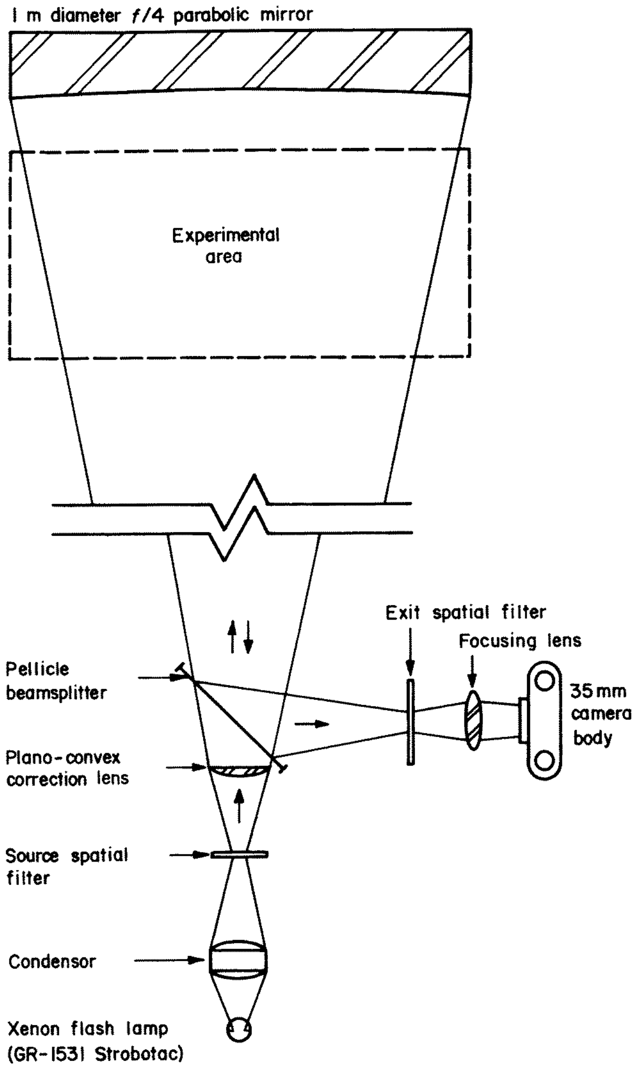

Fig 4 Optical arrangement of double-pass coincident colour schlieren system

this boundary layer and obtain a density profile which is in good agreement with probe measurements. The equations and procedure of such an analysis can be found in any of several cited references[1,6,12,31].

Other compressible-flow applications of colour schlieren include hypersonics[37,107], unsteady flows in shock tubes[51,148], and the ballistics of projectiles in flight[48,64,113,114,119]. The latter application is illustrated in Plate 2, which shows the muzzle blast of a .22-calibre rifle and the emergence of a high-velocity bullet. This photograph was taken with a double-pass, coincident schlieren system using a microsecond strobe light source and a single 1 m diameter parabolic mirror (Fig 4). The two-dimensional dissection colour mask scheme was used, with the background biased toward the yellow. A correction lens[149] is required in the optical train to provide even background illumination, since a spherical mirror should be used in principle but none was available. The microphone used to trigger the photograph is visible in the lower left corner of the frame. This photograph is a good example of colour contrast between the schlieren field and opaque objects, especially the bullet. Many studies of ballistic and explosive events are possible with such equipment[119].

Finally, colour schlieren techniques have been very useful in the analysis of complex aerodynamic flows over flight vehicles[81,85,91], from the post-World War II expansion of high-speed aeronautics[150] to the more recent development of the Space Shuttle[81,117,118]. Plate 3 is an example of transonic flow over an early Shuttle Orbiter model obtained by the two-dimensional dissection colour schlieren technique. The concentric rings in this photograph are not flow features, but are pouring rings in the 2 m diameter wind tunnel windows.

Convective heat transfer

In addition to general references on this subject[1,8,67,162], several detailed quantitative analyses of free convective boundary layers have been conducted[1,62,65,74,94,96] using colour schlieren techniques of the band- or ring-lattice type. Typical examples are shown in Plates 4 and 5.

Plate 4 shows free convection about a heated horizontal cylinder of 2 cm diameter[74]. A vertical band lattice was used as a source filter with a slit cut-off. The temperature profile between the known values of ambient and cylinder wall temperatures was accurately determined by integration across the boundary layer on a horizontal line passing through the cylinder axis. Though this is a relatively simple case, the same approach might be used to advantage in the study of complex heat exchanger geometries.

Plate 5 depicts a 1/10 scale model of a solar-heated room[94]. At the left-hand side is a vertical 'Trombe wall' which accepts solar energy through a transparent outer glazing and later convects it to the room. There is a narrow gap between the glazing and the Trombe wall at the left, and on the right about half of the model room is shown due to the limited size of the schlieren mirrors. To achieve dynamic similarity between this model and its full-scale counterpart a Rayleigh number match is required. This was accomplished by using trichloroethylene as the working fluid in the model; in retrospect, water would have been an adequate and wiser choice. Schlieren results were obtained with a ring-lattice cut-off and were analysed quantitatively as described earlier. At the onset of solar heating, convection currents were observed to travel up the Trombe wall and across the ceiling in a criss-cross motion, eventually establishing the vertical temperature stratification indicated by horizontal isochromes in the photograph. The room temperature distribution found by the schlieren analysis agreed well with that measured by thermocouples. This is a good example of how fluid scale-modelling[78,94] can be applied to a wide range of large-scale heating, ventilation, and air conditioning problems.

Other heat transfer applications include basic studies of convection from horizontal surfaces[103-105], boiling phenomena[63,75], and the free and forced convective flows about living subjects[34,60,61,117,120]. An example of the latter is shown in Plate 6 which shows a young girl seated with a cup of hot liquid in her hand. The convective boundary layer and thermal plume of the body are clearly shown, as is the extensive heat loss from the lap. The two-dimensional dissection colour-coding scheme was used in this case, along with the 1 m parabolic mirror described earlier. Beginning with the pioneering work of Lewis[60] and Clark *et al*[61], such schlieren studies have been important in gaining a better understanding of the interface between the air and the human body. Such issues

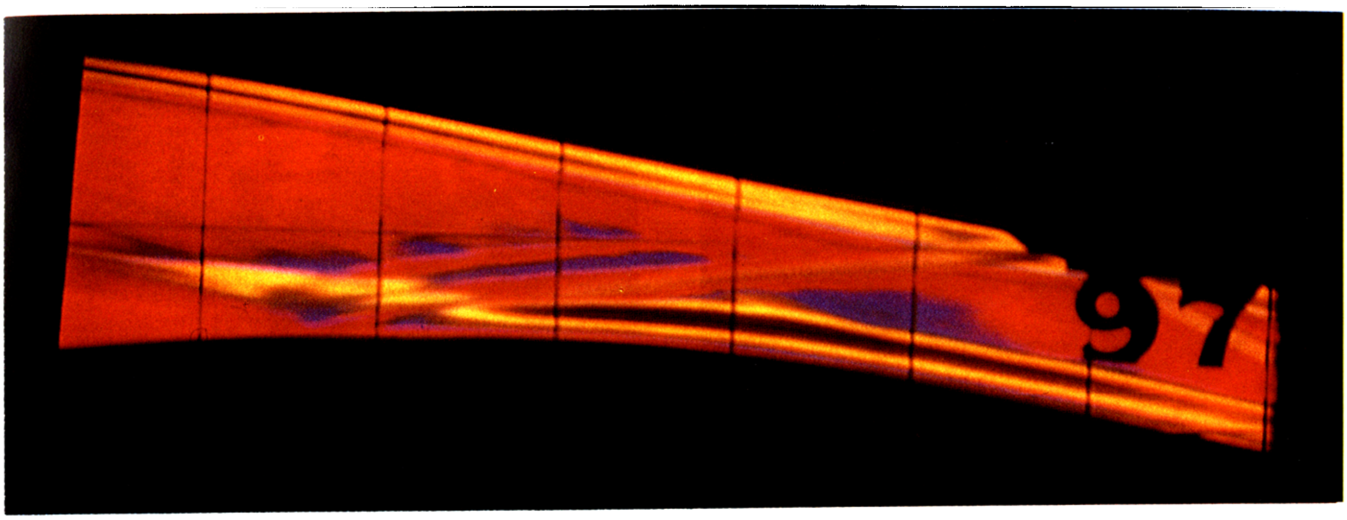

Plate 1 Supersonic inlet flowfield

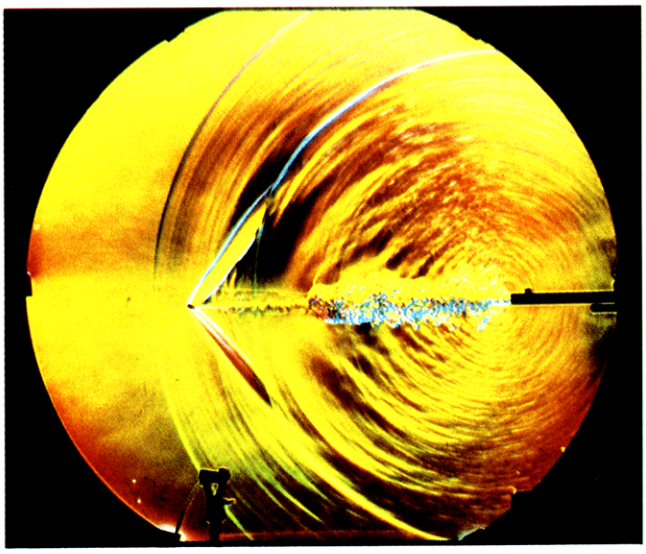

Plate 2 Rifle bullet and muzzle blast

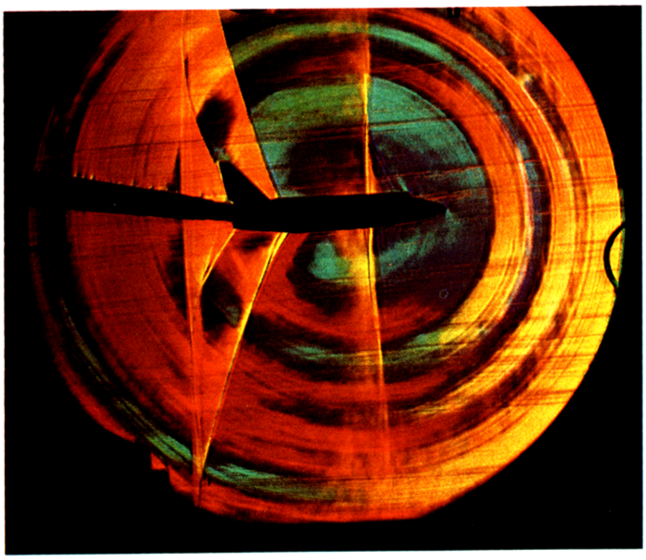

Plate 3 Transonic flow over space shuttle orbiter

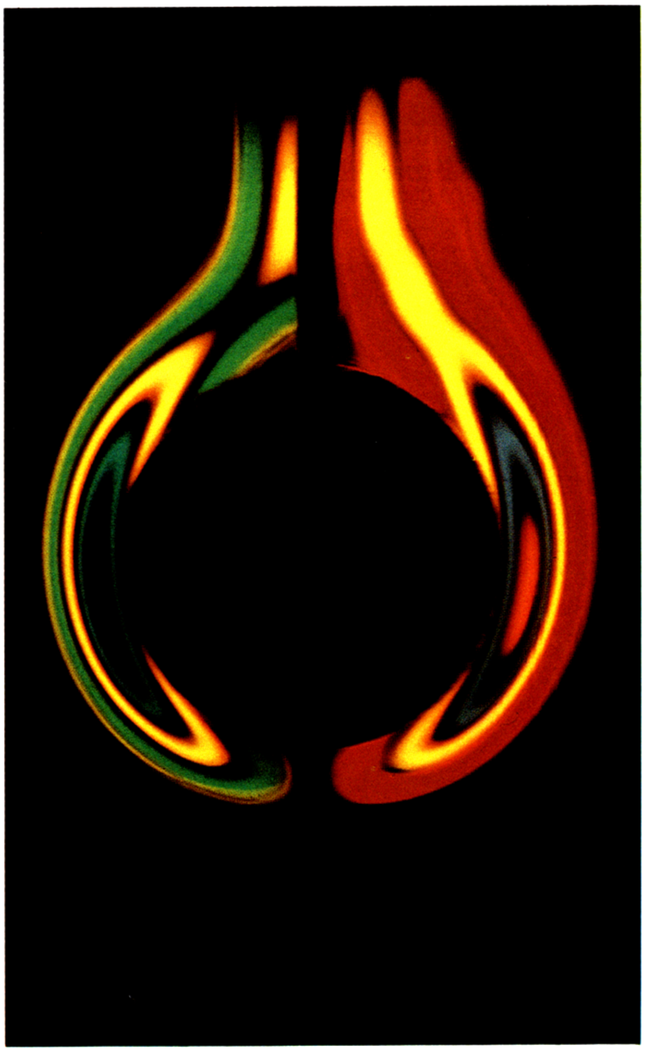

Plate 4 Free convection about heated horizontal cylinder

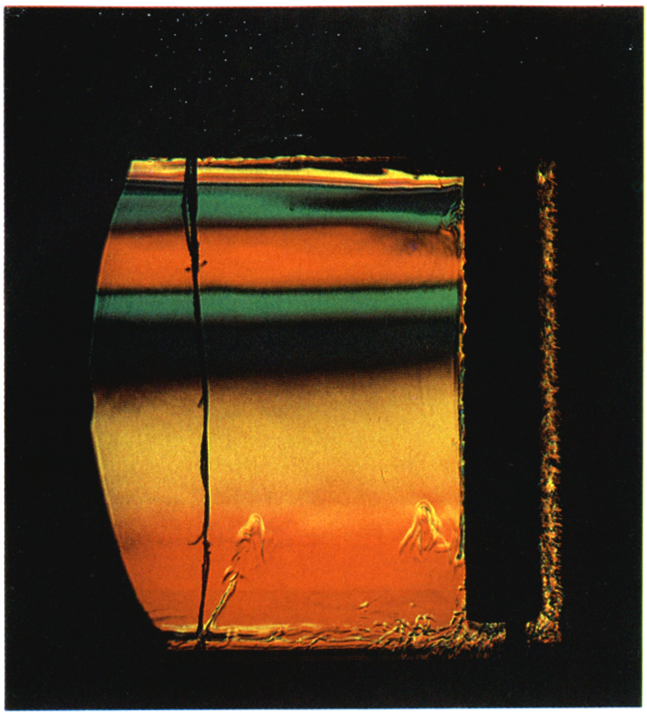

Plate 5 Thermal stratification in solar-heated room model

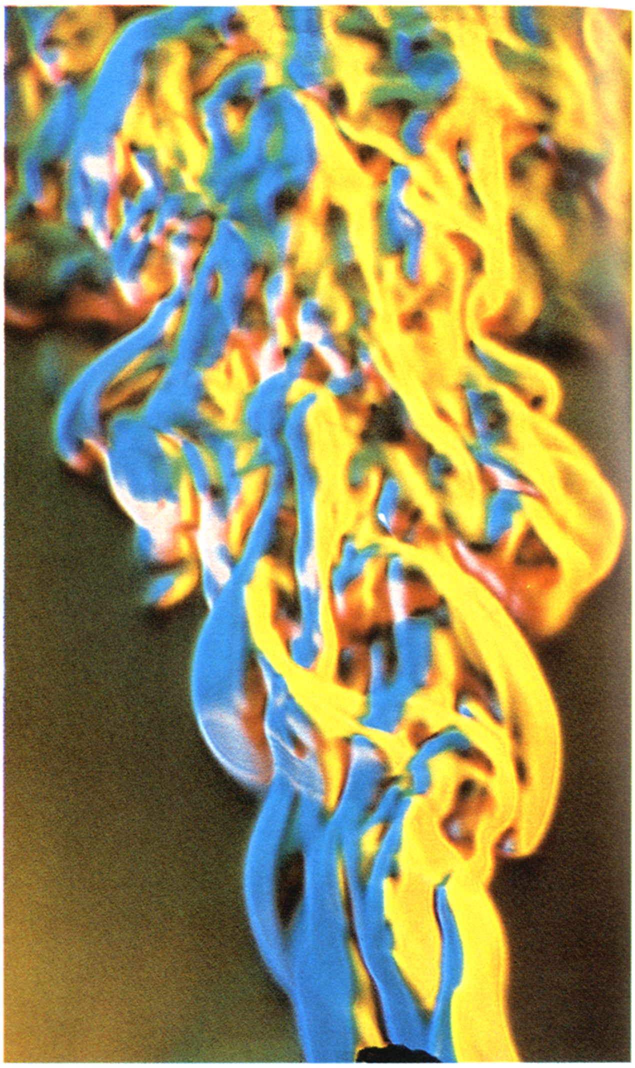

Plate 7 Turbulent flame and convection column

Plate 6 Free convection generated by the human body

Plate 8 Downflow in an industrial clean-room work station

as thermal comfort, protective clothing, skin-flake contamination, the airborne spread of infections, and pulmonary problems may be addressed by such visualisations[120].

Combustion

The optical study of flames has been thoroughly discussed by Weinberg[13]. Colour schlieren techniques are useful here for reasons already mentioned, and especially in that they make it easier to distinguish the coloured schlieren field from the self-luminosity of the flame. In the study of turbulent flames[53,69-72,151], the two-dimensional colour schlieren techniques provide a special advantage in helping to sort out the contortions of the flame front. An example is shown in Plate 7 of the turbulent flame and convection column rising from a burning sample. This photograph was made with the two-dimensional dissection technique, the predominant yellow and blue colours being due to the vertical orientation of those two bands in the rectangular source mask.

The tricolour cut-off filter has similarly proved useful in the visualisation of solid propellant combustion[36,46,47]. Other combustion phenomena which have been observed by colour schlieren include droplet burning[152] and combustion in a supersonic stream[153]. The moiré technique of Weinberg and Wong[142] for large-scale fire-spreading research is adaptable to a pseudo-coloured readout by way of Fourier optical processing.

Fluid mixing

The applications discussed thus far have involved either compressible flow-induced density gradients or temperature gradients. The other possibility of inducing a change in the refractive index of a fluid occurs in the mixing of different species of gases[78,111,117], liquids[84,96,131], or two-phase flows[63]. Phillips[78], for example, obtained quantitative results on the mixing of methane and air in mine safety problems using a band-lattice colour schlieren arrangement with a scale model. Investigations of turbulent mixing[96], stratified flows[131], and chemical diffusion phenomena are other possible applications.

Other applications

The ultrasonics technical community has chosen colour schlieren optics[125-130] as a way of visualising beam paths and their interactions with solid objects. Such ultrasonic beams act as optical phase gratings, causing spectral dispersion in the schlieren cut-off plane. The simple 'isochromate' technique discussed earlier seems to have been used exclusively in this applications so far, though some of the microscopic colour schlieren approaches for dispersive test subjects might also be used to advantage.

In microscopy[14,15,25,92,93,95,97,100,123,124,135], colour schlieren arrangements of various types have been used for almost a century for colour contrast in general and optical 'staining' of live subjects in particular. Zernike's phase contrast method seems to have superceded Rheinberg's original developments in this field in recent years. An excellent summary of colour-coding in microscopy is given by Delly[26].

Glass testing[1,73,86,87,121,122,136], though outside the scope of this survey, has been another traditional application of colour schlieren techniques for over a century.

Among miscellaneous applications are those of acoustic wave visualisation in fluids ranging from air[138] to liquid helium[154], the observation of liquid surface waves[1,118], plasma diagnostics[55], and the use of colour schlieren results for teaching and demonstration[44,155]. The latter application is a most important one: I have observed that colour schlieren illustrations such as Plates 1–8 help students overcome the misconception that fluid mechanics and heat transfer are boring, intangible subjects.

It appears that colour schlieren optics have at least one commercial application in the form of the colour television light-valve projector[156,157]. An oil film distorted by the beam of an electron gun serves as the schlieren object in this case. Most current commercial models actually use three separate projectors in the primary colours, with registration of the three resulting images on the screen. It should be clear from an understanding of Fig 3 that this is an unnecessary complication. In fact, at least one patent[158] proposes to combine the three beams using masking techniques similar to those discussed here, though it appears that this simplification has not yet been included in commercial models.

Finally, a new application of colour schlieren optics, the study of industrial clean-room aerodynamics, is illustrated in Plate 8. Here, a clean-room worker in special garments sits at a work station beneath a down-flow of ambient air at about 0.5 m/s. Under colour schlieren observation, the flow is seen to separate from the worker's forehead, creating a free shear layer which attaches to the horizontal work surface. Thus the work and the upper part of the worker's body bound a recirculation region in which particulate contamination from the body is continuously circulated over the work. This undesirable situation and many others like it were unknown before the study illustrated by the Plate 8 was carried out. Given the current thrust of the microelectronics industry toward lower contamination levels for a greater product yield, such flow studies are clearly important. It has already become apparent in the course of this work that ventilation flows at 0.5 m/s are very tricky, and that no current clean-room equipment has been designed with an understanding of the fluid dynamics involved.

Conclusions

A review of the literature on colour-coding schlieren techniques and applications has revealed over 150 citations, in which more than a dozen distinct techniques have been developed and used. These techniques have been classified in terms of their matched pairs of source and cut-off light masks and their useful applications.

Most of the cited applications take advantage of colour coding and colour contrast in visualising complex refractive fields. The resulting images thus convey more information than would monochrome images, justifying the additional effort involved in the colour visualising. While the primary goal of the majority of the cited studies was a qualitative understanding of the flow, several examples of quantitative colour schlieren results are cited as well. It seems clear that the possibilities for useful colour filtering schemes have not yet been fully explored.

This review has attempted to present a unified view of the diverse techniques of colour in the schlieren instrument and its range of applications in heat transfer and fluid flow. This information should be useful in deciding if colour schlieren visualisation is applicable to a particular application, and, if so, which technique to use. A historical perspective on the techniques and a review of some basic optical principles have been included as well.

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BOOK REVIEW

Heat Transfer

Ed. N. M. Farukhi

This American Institute of Chemical Engineers (AIChE) symposium volume contains most of the AIChE sponsored session papers presented at the 21st National Heat Transfer Conference at Seattle in August 1983. Of the 54 titles, 48 are full papers and 6 are in abstract form in this 438 page softbound volume.

The nine topical areas covered are predominantly multiphase heat transfer oriented, including:

- Two-phase flow in nuclear reactors (6 papers)
- Heat transfer in degraded nuclear reactor core (9 papers)
- Thermal analysis of steam generators (4 papers and 2 abstracts on films)
- Multiphase syn-fuels heat transfer (5 papers)
- Computational techniques in two-phase flows (3 papers)

Other sessions dealt with the following topics, also involving multiphase heat transfer:

- Enhanced heat transfer (5 papers and 1 abstract)
- Process heat transfer (6 papers)
- Numerical methods in heat transfer and fluid flow (8 papers)
- Heat transfer in glass (3 abstracts and 2 papers)

In this brief review it is not possible either to list all the paper titles nor to comment on these papers individually. Some selected groups, however, will be discussed.

The steam generator sessions had as a common thread the computer codes developed for thermo-hydraulic analysis of recirculating U-tube and once-through nuclear steam generators. This included use of the steam separators as flow meters for two-phase fluids; thermal-hydraulic tests involving feed flow oscillation and comparison with analytic predictions; and computer code verification using actual steam generator data.

Several of the papers in the session 'two-phase flow in nuclear reactors' dealt with the prediction and behaviour of two-phase flows in pipes and passages. These ranged from prediction of two-phase critical flow in porous media flow, to counterflow and reflooding.

The papers on enhanced heat transfer dealt with the performance of external and internal extended surfaces in flow passages. Test results using freon in various configurations are reported for T-finned tube exteriors, artificial cavity surfaces, and fouled horizontal surfaces. Correlations are proposed in most of the papers.

The book is one of a series of bound volumes covering the AIChE papers at its annual heat transfer conferences and as such it deserves to be in the library of every serious practitioner of multiphase heat transfer, whether involved in the nuclear or in the process industry. It is also of interest to the academic community; it provides analytical and experimental results of potential use to the researcher and the teacher. For both groups the book provides up-to-date technical information and, it should be noted, it represents roughly one third of the papers presented at the conference, with the other two-thirds printed in topical volumes or in single pamphlet form by ASME, the conference cosponsor.

The book was prepared from author-prepared copy and is quite legible. The figures and tables are clear and easy to read. As a regular attendee at these conferences I have copies of this and most of the previous symposium volumes. I find them a valuable reference and evidence that we are increasing our heat transfer data base as well as our understanding of heat transfer.

E. Fried
General Electric Company,
Schenectady, New York,
USA

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