Athermalized color correction in glass-liquid optical systems

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ABSTRACT

The incorporation of abnormal dispersion liquids into an optical design can result in significant performance advantages. However, the large thermal coefficient of refractive index which is common to all liquids (dn/dT) can complicate the athermalization of these designs. One method is to use two different liquids to form both positive and negative liquid lens elements with balance each other thermally while maintaining color correction. The success of this approach is dependent on the proper selection of materials, and on a detailed knowledge of the wavelength dependence of the refractive index thermal coefficients.

The thermal dependence of refractive index and dispersion in the visible spectral region for a number of liquids was investigated. A correlation between the refractive index thermal coefficient (dn/dT) and abnormal dispersion was found to exist in a majority of liquids.

The optical property measurements were made at the Vavilov State Optical Institute, St. Petersburg, Russia, in collaboration with the Lockheed Palo Alto Research Laboratory, Palo Alto, California.

Keywords: refractive index, abnormal, dispersion, liquid, thermal coefficient of refractive index.

INTRODUCTION

Designing apochromatic lens systems requires incorporation of abnormal dispersion materials. The more abnormal any material is the more useful it is in the design of apochromatic lens system. Due to physical-chemical and structural features, optical liquids appeared to have unique abnormal dispersion properties as compared with those of glasses and crystals. Abnormal dispersion is a property which originates from the shape of a dispersion curve in the visible spectral region.

At present it is conventional to display abnormal dispersion characteristics of materials with Buchdahl dispersion plot [1,2]. In Figure 1 we plotted the primary and secondary Buchdahl dispersion coefficients for Schott optical glasses and a number of optical liquids. The composition of liquids #295990, #400513, #550206, and #642134 has either been described previously[1], or is considered proprietary.

Materials which have a common correlation between the refractive index and dispersion over the visible spectral region are known as normal dispersive. The majority of optical glasses are found to be normal. In Buchdahl dispersion map they lie along the straight line which is called the "Normal line".

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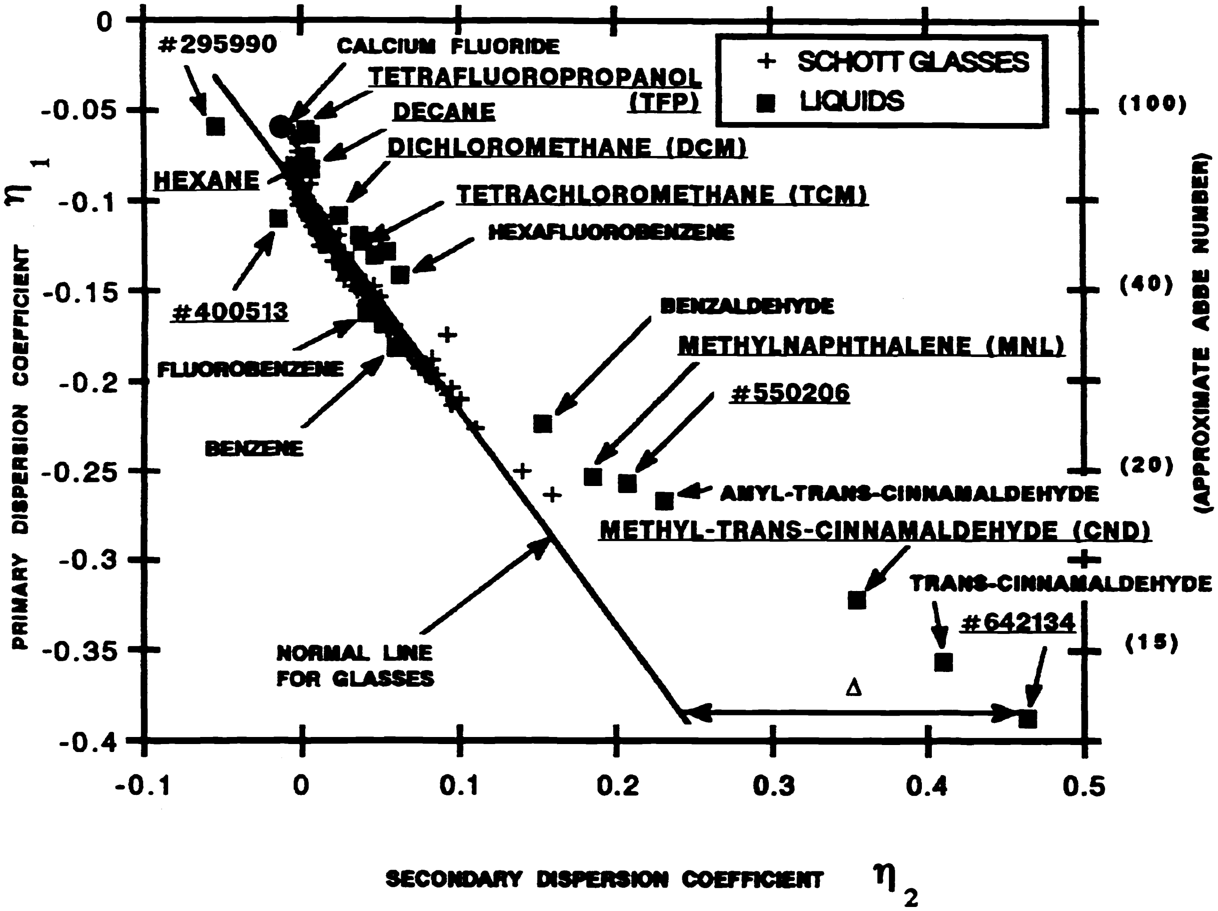

Figure 1. Buchdahl dispersion map for glasses and liquids.

Materials that lie off the normal line are considered to have abnormal dispersion, and by tradition they are referred to as abnormal. The greater the deviation of any material from this normal line (Δ), the more abnormal the material is said to be, and the more successfully a chromatic aberration of lens systems can be corrected.

However, liquids have one more very unusual optical property. The refractive index thermal coefficients (dn/dT) of liquids are negative and large by the absolute value. To maintain color correction of lens systems with liquid elements successfully it is necessary to investigate wavelength dependencies of the refractive index thermal coefficients.

EXPERIMENTAL PROCEDURE

We have obtained the refractive index thermal coefficients (dn/dT) for about 20 organic liquids from the visible spectral region to infrared (IR). As before[3] the refractive indices were measured at three different temperatures (about room temperature (RT), and plus or minus 9°C (RT±9)). The data were linearized by the least square fit and the values dn/dT were calculated. Our refractometry facilities including two goniometers of similar type and identical thermal stabilization cells - one for the visible and the other for IR have been already reported in detail[3]. The accuracy of refractive indices measurements is ±0.00001 over the wavelength range from 0.4047 to 1.5 μm, and ±0.00005 at 1.6 μm. The temperature of the liquids was measured to the accuracy of ±0.01°C. The accuracy of dn/dT calculations is ±0.00001.

RESULTS

In Figure 2 (a, b) we present dn/dT data for 10 liquids. The refractive index thermal coefficients (dn/dT) of all liquids are known to be negative and high by the absolute value which is determined by the fact of great value of thermal expansion.

To compare the behavior of dn/dT versus wavelength for different liquids the special ordinate axis is used in Figure 2 (b). The ordinate axis shows the difference between dn/dT at a given wavelength and dn/dT at the line r (λ=0.7065 μm). We shall refer to it as difference of dn/dT. By this way we can compare curve shapes for all liquids studied. We have already used this graphic technique previously to compare the dispersion curve shapes of different liquids[4].

Most of liquids studied appear to have a linear dn/dT versus wavelength. The difference between the values dn/dT at the lines h (λ=0.4047 μm) and r (λ=0.7065 μm) as small as $2\text{-}3\times10^{-5}$ regardless of the fact that absolute values of dn/dT for different liquids range from -3×10^{-4} to -7×10^{-4}. So in Figure 2 (b) the data for the majority of liquids lie very close to one another while in Figure 2 (a) the spacing between the curves are large.

Four of the liquids studied have unusual dependencies of dn/dT versus wavelength. The differences between the values dn/dT at the lines h (λ=0.4047 μm) and r (λ=0.7065 μm) for these liquids are 19×10^{-5} (liquid #642134), 9×10^{-5} (liquid CND), 9×10^{-5} (liquid #550206), and 7×10^{-5} (liquid MNL). The refractive indices for the liquid CND were measured beginning from the line g (λ=0.4358 μm) due to the low violet transparency of this liquid, so the dependence of dn/dT for this liquid stops at λ=0.4358 μm.

In Figure 2 (b) these four liquids are located some upper than other liquids. Liquid #642134 which is the unique liquid in dispersion properties is the most unusual from the point of view of dn/dT versus wavelength also.

It appears that liquids which are practically normal have weak wavelength dependencies of dn/dT regardless of wide variation of dn/dT values of these liquids. For example, liquid TFP is a normal liquid (as compared with other ones, Figure 1), it has small values of refractive index and practically flat curve of dn/dT. On the other hand, liquid DCM has also very flat curve of dn/dT, but the value of its dn/dT is two times greater than for the first one (Figure 2).

On the contrary, liquids with great abnormality in the visible region have a significant slope of their curves of dn/dT versus wavelength, for example liquid #642134 has the largest slope of the dn/dT curve.

The large modules of dn/dT of liquids can complicate the athermalization of optical designs with liquid elements. To understand whether we can modify the values of dn/dT of liquids we made the following tests.

It was shown that we can change the absolute values of refractive indices of liquids affecting on their UV absorption bands with UV irradiation[5]. We compare dn/dT data of a non-irradiated and irradiated liquids.

Figure 3 (a, b) shows the dependencies of dn/dT versus wavelength for two abnormal liquids proven to be quite useful in the design of apochromatic optical systems for the visible and ultraviolet spectral regions. For each liquid we present data for non-irradiated and irradiated samples. The experimental conditions of irradiating liquids were described in detail in Ref.[5] In Figure 3 (b) we also use the special relative ordinate axis similar to Figure 2 (b).

Liquid #642134 was irradiated during 45 minutes, and this irradiation produced the shift of the absorption edge of this liquid towards the long wavelengths by about 40 nm at the point of 60% transmission and by about 20 nm at the point of 50% transmission as compared with the absorption edge of the non-irradiated liquid. Liquid #550206 was irradiated during 2 hours, after exposure the resulted absorption edge shift is nearly 75 nm at the point of 50% transmission[5]. These exposures were limited by minimal resulting transmission of a liquid required for refractive index measurements after irradiation. Our goniometer technique required at least 40% transmission along over the optical path of the measuring prism (30 mm)[5].

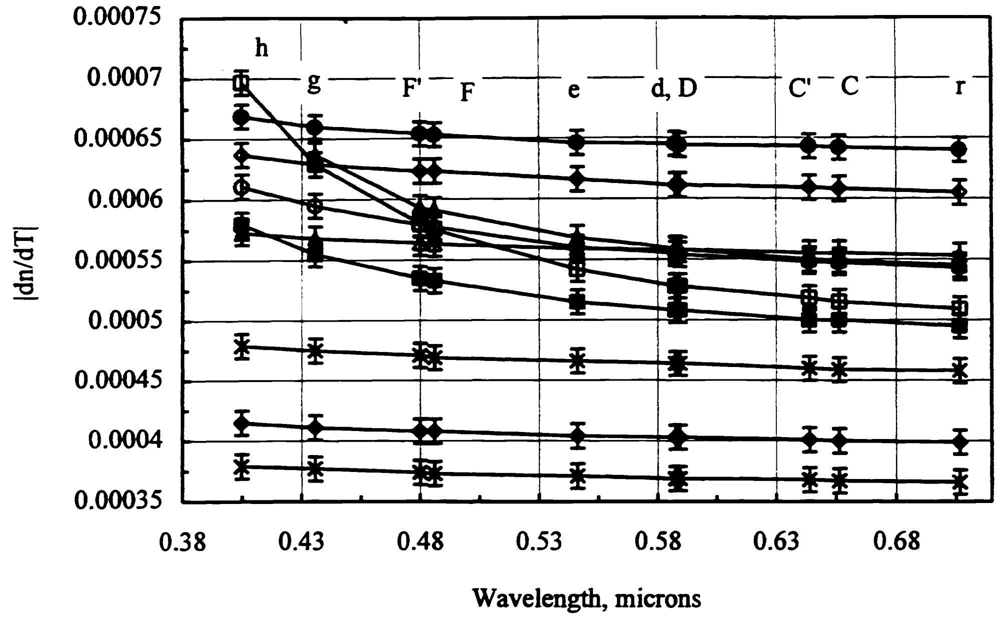

Figure 2, a. Module of dn/dT versus wavelength for liquids.

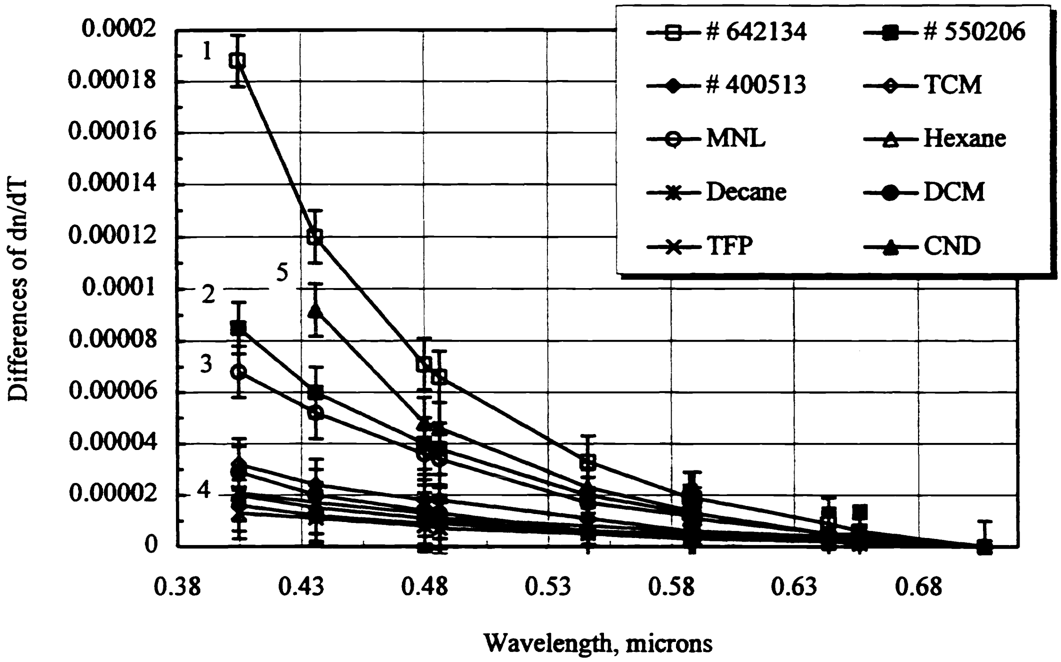

Figure 2, b. Differences of dn/dT versus wavelength from λ to λ_r (0.7065 μm).

The following designations of pure chemicals are used:
TCM - Tetrachloromethane,
MNL - Methylnaphthalene,
DCM - Dichloromethane,
TFP - 2,2,3,3-Tetrafluoro-1-propanol,
CND - Methyl-trans-cinnamaldehyde.

1 - #642134, 2 - #550206, 3 - MNL, 4 - the group of liquids: Hexane, Decane, DCM, TCM, TFP, #400513, 5 - CND.

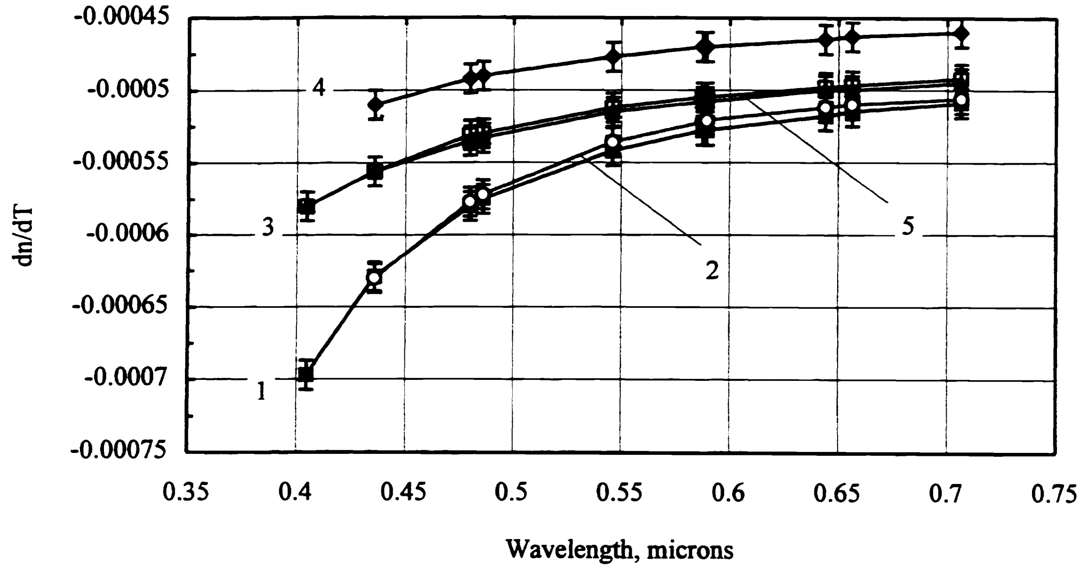

Figure 3, a. dn/dT versus wavelength for two liquids.

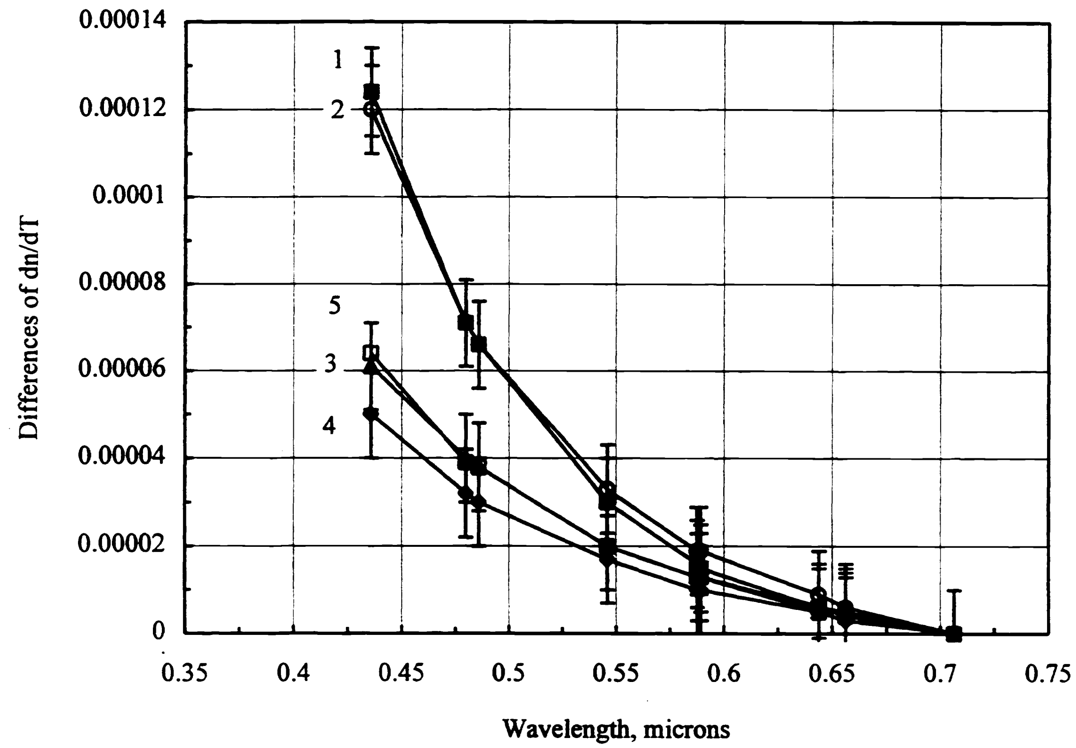

Figure 3, b. Differences of dn/dT versus wavelength from λ to λ_r (0.7065 μm).

Curve 1 - dn/dT of the non-irradiated liquid #642134,
Curve 2 - dn/dT of the irradiated liquid #642134,
Curve 3 - dn/dT of the non-irradiated liquid #550206,
Curve 4 - dn/dT of the liquid #550206-*Hb* ,
Curve 5 - dn/dT of the irradiated liquid #550206.

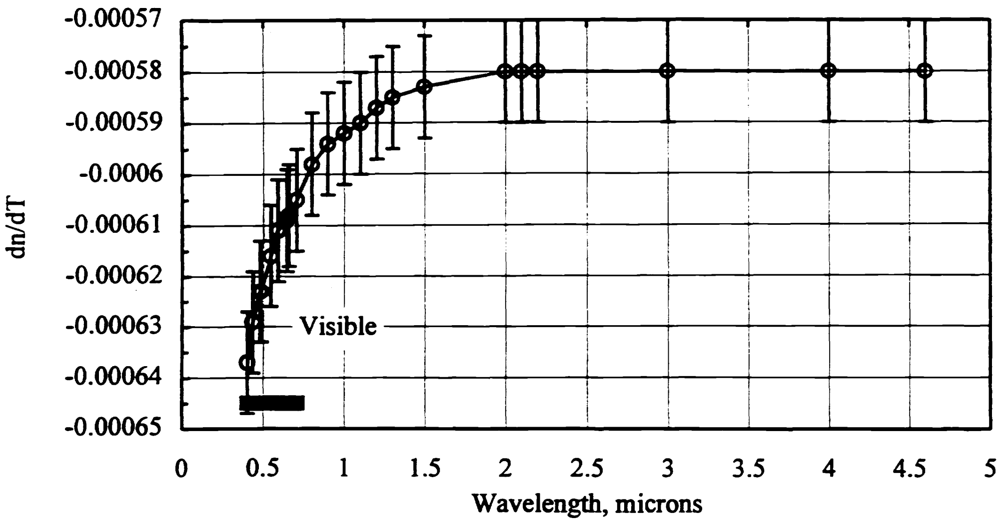

Figure 4. dn/dT versus wavelength for Tetrachloromethane liquid.

The shifts of the absorption edges of liquids resulted also in decreasing the number of wavelengths where the refractive indices could be measured. So both irradiated liquids were measured in the range beginning from the line g (λ=0.4358 μm).

As it is seen the absolute values of dn/dT of both liquids decrease after exposure to the intense UV irradiation, but this decrease is practically negligible (Figure 3, a, curves 1 and 2, 3 and 5). The dependencies of dn/dT versus wavelength for both liquids do not change after irradiation (Figure 3, b).

Curve 4 in Figure 3 presents the data for the liquid #550206-*Hb*. This liquid is primarily liquid #550206, and the main properties of this liquid are reported in Ref.[6] As it can be seen the absolute value of dn/dT of the liquid #550206-*Hb* is less by about 5×10^{-5} compared to the liquid #550206.

We have obtained the refractive index thermal coefficients for all liquids studied over the useful transmission range of each liquid. In Figure 4 we present the dn/dT data for TCM liquid from 0.4047 to 4.6 μm. According to our data it changes strongly up to 1.5 μm and is practically constant at longer wavelengths.

In Ref.[1] was shown that the athermalization method of lens designs with liquids incorporated exists. This method assumes using a couple of different liquids to form both positive and negative liquid lens elements which balance each other thermally while maintaining color correction. The success of this approach is dependent on the proper selection of materials. To answer the question if it is possible to find a couple of liquids with similar spectral behavior of dn/dT and at the same time with greatly different abnormal dispersion we compare dn/dT data with the abnormal properties of liquids studied.

Figure 5 presents a diagram of the abnormality versus the difference of dn/dT for 10 liquids. In this Figure the "abnormality" is the difference between the secondary dispersion coefficient of a liquid and the secondary dispersion coefficient of a point which is lying on the normal line and has the same primary dispersion coefficient:

$$\Delta = \eta_2\,(\text{liquid}) - \eta_2\,(\text{normal line})$$

This difference which characterizes the abnormal dispersion of a liquid is referred to as abnormality of a liquid. For example, in Figure 1 we show the abnormality (Δ) for the liquid #642134.

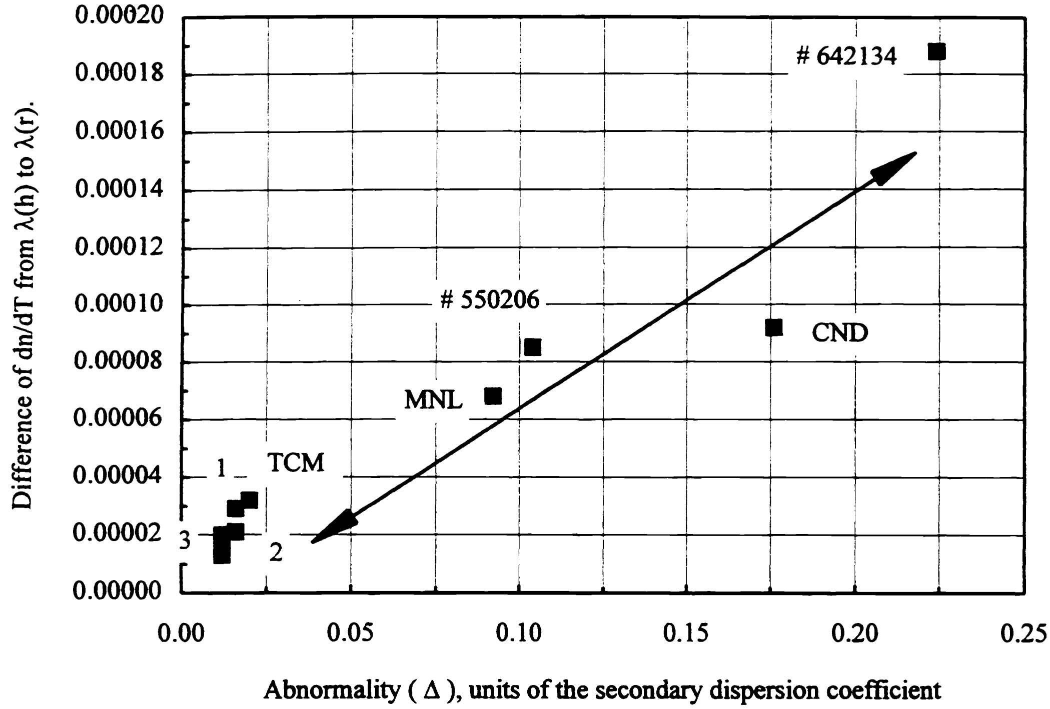

Figure 5. Abnormality (Δ) and the difference of dn/dT for liquids.
The following designations of pure chemicals are used:
TCM - Tetrachloromethane,
MNL - Methylnaphthalene,
DCM - Dichloromethane,
TFP - 2,2,3,3-Tetrafluoro-1-propanol,
CND - Methyl-trans-cinnamaldehyde.
1 - DCM, 2 - Decane, 3 - the group of liquids: Hexane, #400513, TFP.

In Figure 5 the ordinate axis is a difference between dn/dT at the lines h (λ=0.4047 μm) and r (λ=0.7065 μm). Difference of dn/dT characterizes the shape of dn/dT spectrum.

We found that some correlation between the difference of dn/dT over the visible region and the abnormality (Δ) exists for liquids. Liquids with large difference of dn/dT are very abnormal ones. In other words, the more abnormal is a liquid the more it's dn/dT depends on wavelengths. Liquid #642134 has very unique abnormal properties in the visible, and at the same time it has the great difference of dn/dT. In Figure 5 it is in the upper right hand corner. Liquids CND, #550206 and MNL have large abnormality (Δ), and also large difference of dn/dT over the visible region.

On the contrary, those liquids which have small difference of dn/dT over the visible region appear to have very small abnormal dispersion. Liquids Decane , Hexane, DCM, TFP have only slight difference of dn/dT, and they are very close to normal (as compared with liquids #642134, for example).They cluster around the lower left hand corner very close one to another (Figure 5) regardless of considerable difference of their dn/dT values.

The correlation described holds for all liquids studied (Figure 5).

To summarize, if any liquid has a large difference of dn/dT over the visible region, it is also the abnormal dispersive one. If any liquid has a small difference of dn/dT, this liquid is only slightly abnormal.

CONCLUSIONS

The thermal dependence of refractive index and dispersion in the visible spectral region for a number of organic liquids was investigated.

The refractive index thermal coefficients of two abnormal liquids #642134 and #550206 were found to be unaffected by the intense UV irradiation.

It is shown that some correlation between the wavelength dependence of dn/dT and abnormal dispersion exists in the majority of liquids studied. The larger the difference of dn/dT of a liquid over the visible spectral region, the more abnormal it is. The smaller the difference of dn/dT, the less abnormal this liquid is.

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