Transformation of colour space dedicated to an experimental analysis fulfilling the applicability criteria

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Abstract. The choice of colour space is very important in the digital image analysis by reason of accuracy and computational time. Particle Image Velocimetry and Particle Image Thermometry are the optical methods commonly applied in the fluid dynamics and heat transfer. Especially in PIT method, the analysis of colour images is significant. In this paper, transformation of RGB to HSI colour space dedicated to PIT will be presented. Derivation of formulas together with its graphical representation will be discussed. Fulfilment of applicability criteria will be shown. This theoretical approach to digital image processing supplements the knowledge about the optical experimental methods.

1. Introduction

Digital Particle Image Velocimetry (DPIV) or Thermometry (DPIT) are the methods often applied in the experimental analysis nowadays. Both of them depend on the image analysis but DPIT depends also on the colour analysis. DPIV enables determination of temperature field on the basis of cross-sectional images of Thermochromic Liquid Crystals (TLC) response representing the temperature field and indirectly the fluid flow. TLC particles reflect part of the illuminating them white light in dependence on their temperature and illuminating angle. In the reflected light dominates particular wavelengths, therefore it is possible to use the Charge Coupled Device (CCD) in the temperature determination process. CCD element records the electrical signals of strength proportional to the amount of incident light [1]. The calibration curve represents the dependence of dominant reflected wavelength and the temperature. The crucial point of analysis is to find such function. The best way, unfortunately the most expensive, is to use the spectrometer. The common way is to analyse the images taken by utilization of some number of selective filters. Characteristics of filters transparency constructs the base vectors of colour space. In typical camera with NTSC system there are three filters of Red (R), Green (G) and Blue (B) colours [1]. In the majority of cases, the R, G, B collection uniquely determines the temperature. Due to that, it is possible to find calibration curve directly – utilizing the R, G, B values or indirectly – applying other function, which is a function of R, G, B components.

DPIT with utilization of RGB colour space or its function were applied in many research areas such as the phase change [2], crystal growth [3], impinging heat transfer [4], convection [5] or medicin [6]. Direct application of the R, G, B colour space components [1, 3-4] caused the calculation difficulties: complex calculation procedure and long calculation process. Therefore the colour space transformation became a common routine in such applications [1-2,5,7]. The RGB colour space
transformation can lead to the reduction of variables number and easier way of calculation connected with lower time consumption.

In the literature there is an absence of derivations and what is more important, there is lack of verification if applied space transformation fulfil the applicability criteria [1]. The aims of this paper are: to derive the formulas of RGB to HSI colour space transformation applied in various research areas [2,5-6], to compare them with the other formulas [8-10] and to check if the applicability criteria are fulfilled by them.

2. Colour space

Three independent signals of \( R, G, B \) belong to the colours space based on the cartesian coordinate system. This space is device-oriented and its origin is coming from the operation of camera sensors or screens [2]. In the digital image analysis more useful are the colour spaces referring to the human colour sensation, like Hue, Saturation, Value (HSV), Hue, Saturation, Lightness (HSL) or Hue, Saturation, Intensity (HSI) spaces. They separate the “colourless” Value (Lightness, Intensity) components from the “colourful” Hue and Saturation ones. In these spaces, Hue depends on the wavelength, which enables differentiation between, for example, the red and yellow colours. Saturation represents “amount” of colour, therefore the difference between the red and pink colours can be distinguished. The third variable – Value, Lightness or Intensity, refers to the amount of light, which enables determination of light and dark colours or the levels of grey.

![Figure 1. Colour wheel.](image1)

![Figure 2. Double cone of RGB gamut.](image2)

The Hue is a property of pure colour, very often identified with the colour itself, which helps to distinguish particular colours among the others. It is closely connected with the light wavelength. On the colour wheel, proposed by Newton, it is represented by angle of pure colour. One of the wheel construction methods places three additive \( R, G, B \) colours in the vertices of one equilateral triangle and three subtractive Yellow (Y), Cyan (C), Magenta (M) colours in the vertices of second equilateral triangle, located above the first one in such a way that complementary colours are symmetrically situated, relatively to the triangles centre (figure 1). They form colour pairs (R-C), (G-M), (B-Y). The corresponding colour angles are as follows \( R = 0^\circ, \ Y = 60^\circ, \ G = 120^\circ, \ C = 180^\circ, \ B = 240^\circ \) and \( M = 300^\circ \) [12]. This hexagonal structure, inscribed in the circle gives the colour circle, in which angle of radius vector indicates pure colour, placed on the circle perimeter. Each pure colour can be represented by a mixture of two neighbouring colours. To illustrate Lightness, the additional parallel circles of decreasing diameter should be added above and below the basic colour circle. The double cone of colour is created (figure 2). The circles placed above the basic circle, tend towards the white colour,
therefore they become lighter. The circles placed below the basic one, tend towards the black colour becoming darker. The axis of such body corresponds to the grey scale from black to white colour and it describes the Lightness axis. Distance between the particular colour and this axis is a measure of Saturation. The angle between the planes containing this axis and the planes containing red colour and any other colour is called Hue [12]. Value can be illustrated by height of inverted cone, while Intensity by diagonal of RGB cube.

3. **RGB to HSI colour space transformation**

As it was already mentioned the crucial point in PIT method is to find the colour-temperature function. In the RGB colour space this function has three variables, so it is not unequivocal or easy to calculate. To reduce the number of variables, the RGB colour space transformation is applied. This transformation is obtained by the geometrical dependences between the RGB cartesian colour space and the space defined by an orientation of colour cube on the xy plane. It should be oriented in such position that its main diagonal is perpendicular to this plane and it defines the Intensity axis. Such transformation described in [1,7,11,13,14] is non-linear, therefore any image analysis is time consuming. There is also one more difficulty coming from the existence of singularity on the plane described by the equation $2R-G-B=0$.

The examples of linear RGB to HSI colour space transformations can be found in the literature. They “linearity” arises from an assumption that in the regions, in which one of the RGB components is maximal, other one minimal, the value of Hue can be approximated by a linear function of third component, equal to the central value. One of such transformations is reported in [8], together with its derivation and geometrical visualization. Instead of the Intensity component, the synonymous component called Value was utilized. Saturation and Hue were defined in particular sextants of colour hexagon. Saturation was zero on the Intensity axis (except the point represented by the black colour, point $K(R,G,B) = K(0,0,0)$) and it was equal to one on the walls and edges (belonging to the planes $RG, GB, BR$) of colour cube. For constant $Value = max(R,G,B)$ in particular sextant of colour hexagon Saturation became linear function of $min(R,G,B)$. The linear transformation of RGB to HSI colour space is also presented in [9], but without any explanation of its origin or derivation. Similar transformation is described in [10] and it is a part of Java Platform, however instead of HSI the identical with it the HSB colour space was used. Comparison between these three transformations indicates their equivalence.

4. **RGB to HSI colour space transformation dedicated to PIT**

The following equations defining Hue, Saturation and Intensity were published in [15,16,17] without any derivation:

$$H = 63 + 63 \cdot (G' - R') \cdot (G' + R')^{-1} \quad for \quad B' = 0, \quad (1)$$

$$H = 189 + 63 \cdot (B' - G') \cdot (B' + G')^{-1} \quad for \quad R' = 0, \quad (2)$$

$$S = 255 \cdot \left(1 - \frac{\min}{I}\right) = 255 \cdot s, \quad (3)$$

$$I = \left(\frac{R^2 + G^2 + B^2}{3}\right)^{1/2}. \quad (4)$$

where: $R' = R - \min$, $G' = G - \min$, $B' = B - \min$, $\min = \min(R,G,B)$, $s$ is a relative saturation.

Presented formulas were derived in the basis of geometrical dependences between RGB and HSI colour spaces. In this transformation the colour components take the values from range $(0,255]$. However, maximal value of Hue is 252, because the colours vary from $H(R) = 0$ corresponding to the red colour, through $H(Y) = 63$ (yellow colour), $H(G) = 126$ (green colour), $H(C) = 189$ (cyan colour) to $H(B) = 252$ (blue colour). This feature is used in the image analysis to record $H, S, I$ values in a sequence of 8-
bit positive integers. Equation (1) and (2) and also (4) defining Hue and Intensity are non-linear. Linear transformation refers only to relative saturation, equation (3).

Colour hexagon RYGCBM presented in figures 3 and 4 can be divided in three rhombus of red RYWM, green GCWY and blue BMWC colours. The other three rhombus can be also found: yellow, cyan and magenta. Each of the rhombus can be divided in the triangles. In the red rhombus there are two triangles: yellow RYW and magenta RWM, in the green one there are yellow GWY and cyan GCW triangles, in the blue – cyan BWC and magenta BMW. Going counter-clockwise the successive triangles are yellow of red rhombus, yellow and cyan of green rhombus, cyan and magenta of blue rhombus and magenta of red rhombus. The values of $R,G,B$ colour components in exemplary triangles are listed in table 1. The following abbreviations are used: $\max = \max (R,G,B), \cen = \cen (R,G,B)$ - central value from $(R,G,B)$ and $\min = \min (R,G,B)$.

| Color of rhombus | Color of triangle | Component |
|------------------|-------------------|-----------|
| red              | yellow            | $R$ max  |
|                  |                   | $G$ cen   |
|                  |                   | $B$ min   |
| green            | yellow            | $R$ cen   |
|                  |                   | $G$ max   |
|                  | cyan              | $R$ min   |
|                  |                   | $G$ max   |
| blue             | cyan              | $R$ min   |
|                  |                   | $G$ cen   |
|                  |                   | $B$ max   |

In PIT method the most important variable is colour, therefore only definition of Hue (equations (1) and (2)) will be derived here.

In the yellow triangle of red rhombus the red component is maximal $R = \max$, while blue is minimal, $B = \min$. When the $\max$ and $\min$ values are constant, Hue is the linear function of central value corresponding to the green component $G = \cen$ in this triangle. For the arbitrary chosen colour, marked in figure 3 (point at the end of arrow), the following formula based on the geometrical dependences can be written:

$$ H = 63 \cdot \frac{G-B}{R-B} = 63 \cdot \frac{(G-B) + (R-B) - (R-B)}{R-B} = 63 \cdot \left(1 + \frac{G'-R'}{R'}\right). \quad (5) $$

Continuing, in the yellow triangle of green rhombus the green component is maximal $G = \max$, while blue – minimal $B = \min$. Again, when the $\max$ and $\min$ values are constant, Hue is the linear function of central value corresponding to the red component $R = \cen$. In figure 4 arbitrary chosen colour (point at the end of arrow) is analyzed.

Hue value for this colour can be calculated as:

$$ H = 63 + 63 \cdot \frac{G-R}{G-B} = 63 \left[1 + \frac{(G-B) - (R-B)}{(G-B)}\right] = 63 \left(1 + \frac{G'-R'}{G'}\right). \quad (6) $$

The equations describing Hue in yellow triangles of red and green rhombus (equations (5) and (6)) differs only in denominator. Derived relations are equivalent to known linear functions [8]. The following relation can be written for entire yellow rhombus, with an assumption that the dominator can be taken as $G' + R'$

$$ H = 63 \cdot \left(1 + \frac{G'-R'}{G'+R'}\right) = 63 + 63 \cdot (G'-R') \cdot (G'+R')^{-1} \quad \text{for } B' = 0. \quad (7) $$
Relation (7) for yellow rhombus \( YGWR \) is equivalent to equations (5) and (6) only on the planes going through \( R, Y \) and \( G \) colours. For other planes they differ as much as \( \pm 10.8 \).

Calculation of Hue for the cyan rhombus \( CBWG \) is analogous, with following substitutions: \( R \rightarrow G \), \( G \rightarrow B \) and \( B \rightarrow R \). The base colour also has to be changed from \( H(Y) = 63 \) to \( H(C) = 189 \). Finally, the relation describing Hue in the cyan rhombus can be written in a form

\[
H = 126 + 63 \cdot \left( 1 + \frac{B' - G'}{B' + G'} \right) = 189 + 63 \cdot (B' - G') \cdot (B' + G')^{-1} \quad \text{for } R' = 0. \tag{8}
\]

Subsequent analysis will be carried out only for the yellow rhombus \( YGWR \), because it can be applied also to the cyan rhombus \( CBWG \). For the simplification of formulas the values of \( R, G \) and \( B \) components will be taken from the range \([0,1]\) – the colour cube becomes unitary. It means that the Saturation and Intensity will be also in this range.

5. Criterion of Hue invariability in a plane containing the Intensity axis

Dedicated to PIT method, \( RGB \) to \( HSI \) colour space transformation should fulfil the criterion of Hue invariability in a plane containing the Intensity axis [1]. Value of Hue in the yellow rhombus \( YGWR \) should come from the range \((0,126)\) and be constant for any plane going through the Intensity axis.

In the triangle \( YWR \) of red rhombus, Hue belongs to the range \((0,63)\). This value should be invariable on the plane containing the black point \( K = (0,0,0) \), white point \( W = (1,1,1) \) and arbitrary chosen point \( X = (1,x,0) \) located at the edge of colour hexagon connecting the points \( R = (1,0,0) \) and \( Y = (1,1,0) \). Variable \( x \) belongs then to the range \((0,1)\). Equation describing such plane takes the form

\[
x \cdot R - G + (1-x) \cdot B = 0 \quad \text{or} \quad x \cdot (R-B) - (G-B) = x \cdot R' - G' = 0, \tag{9}
\]

Which is coming from a general equation of plane. The equation coefficients were determined by solution of the equation system. Value of Hue calculated with equation (1) [15] is equal to the value calculated with equation (5) representing linear method according to Authors derivation, but only for the plane containing \( R \) and \( Y \) colours. Equation (1) becomes non-linear for the planes containing \( X \) colour differently from equation (5), which still remain linear. Equation (1) is non-linear because it is a
function of $G$ component taking the central value. This limitation does not applied in the case of equation (5).

In the triangle $YWR$ of red rhombus for the points belonging to the plane $x \cdot R' = G'$, equation (1) ensure the constant value of Hue because

$$H(x) = 63 \cdot \left(1 + \frac{G' - R'}{G + R'}\right) = 63 \cdot \left(1 + \frac{x \cdot R' - R'}{x \cdot R' + R'}\right) = 63 \cdot \left(1 + \frac{1 - x}{x + 1}\right) = 63 \cdot \frac{2x}{x + 1}. \quad (10)$$

Assuming that $x = idem$, what defines the plane, Hue is invariable, for example $H(0) = 0$, $H(0.5) = 42$, $H(1) = 63$. According to the linear method and equation (5) the Hue can be calculated from the formula

$$H(x) = 63 \cdot \left(1 + \frac{G' - R'}{R'}\right) = 63 \cdot \left(1 + \frac{x \cdot R' - R'}{R'}\right) = 63 \cdot \left(1 + \frac{1 - x}{1}\right) = 63 \cdot x. \quad (11)$$

also ensuring its invariability for $x = idem$. Following values of Hue are obtained for exemplary points: $H(0) = 0$, $H(0.5) = 31.5$, $H(1) = 63$.

Taking the same steps in the analysis of yellow triangle $YGW$ in the green rhombus and the plane going through the black point $K = (0,0,0)$, white point $W = (1,1,1)$ and arbitrary chosen point $X = (x,1,0)$ located between $G = (0,1,0)$ and $Y = (1,1,0)$, where $x \in (0,1)$, the following formula describing this plane can be defined

$$R \cdot x \cdot G + (x-1) \cdot B = 0 \quad \text{or} \quad (R-B) - x \cdot (G-B) = R' \cdot x \cdot G' = 0. \quad (12)$$

Its form was obtained in accordance with the method applied for equation (9).

Equation (1) describing the Hue in the triangle $YGW$ is equivalent to the equation (6) only for the planes containing $G$ and $Y$ colours. It becomes non-linear for the planes containing $X$ colour, because Hue is non-linear function of $R$ component on it, whereas equation (6) is still linear.

The invariability of Hue calculated with equation (1) is ensured for the plane $x \cdot G' = R'$ regarding the equation

$$H(x) = 63 \cdot \left(1 + \frac{G' - R'}{G' + R'}\right) = 63 \cdot \left(1 + \frac{G' - x \cdot G'}{G' + x \cdot G'}\right) = 63 \cdot \left(1 + \frac{1-x}{x+1}\right) = 63 \cdot \frac{2}{x+1}. \quad (13)$$

when $x = idem$, for example $H(0) = 126$, $H(0.5) = 84$ or $H(1) = 63$.

Applying the linear method (equation (6)) the invariability of Hue is ensured in whole range

$$H(x) = 63 \cdot \left(1 + \frac{G' - R'}{G'}\right) = 63 \cdot \left(1 + \frac{G' - x \cdot G'}{G'}\right) = 63 \cdot \left(1 + \frac{1-x}{1}\right) = 63 \cdot (2-x) \quad (14)$$

$x = idem$, for example $H(0) = 126$, $H(0.5) = 94.5$ or $H(1) = 63$.

6. Criterion of Hue independence on the Intensity and Saturation

According to [1] the RGB to HSI colour space transformation is suitable for PIT method when the Hue is independent on the Intensity and Saturation.

The independence of Hue on the Intensity can be proved by multiplication of arbitrary chosen colour $X = (R,G,B)$, placed beyond the Intensity axis, by the value $I \leq m \leq \left[\max(R,G,B)\right]^{-1}$. It gives a new colour $\widehat{X}$ located inside the colour hexagon. This new colour should have higher value of Intensity, but the same Hue.

The independence of Hue on the Saturation can be proved by mixing an arbitrary chosen colour $X = (R,G,B)$ with white colour $W = (1,1,1)$ leading to decreasing value of Saturation, but without changing the Hue. Mixing can be obtained by adding to $X$ colour components positive value $a$ from the range $0 \leq a \leq 1 - \max(R,G,B)$. The new colour is creating and it is located on the axis parallel to the Intensity axis, inside the colour hexagon.
Another way of verification is to add “some amount” of colour $X$, $m_X$ to an “amount” of white colour $m_W$ and obtained an “amount” of colour $Z$, $m_Z$ placed between colours $X$ and $W$

$$m_X \cdot X + m_W \cdot W = m_Z \cdot Z \Rightarrow (1-w)\cdot X + w\cdot W = Z \quad \text{or} \quad X + w\cdot(W-X) = Z,$$

where $w = m_W \cdot (m_X + m_W)^{-1}$, $w \in (0,1)$, represents an amount of added white colour $W$ in colour $Z$.

If two of these three requirements are fulfilled, the criteria of Hue invariability in the plane containing the Intensity axis (chapter 4) is also fulfilled.

The Intensity of colour, obtained by multiplying the colour $X$ by value of $m$ ($m \geq 1$) is increasing

$$I (mR, mG, mB) = \left[ \frac{(mR)^2 + (mG)^2 + (mB)^2}{3} \right]^{1/2} = m \cdot I (R, G, B),$$

the Saturation does not change, attention: in subsequent derivations, relative Saturation $s \in [0,1]$

$$s (mR, mG, mB) = 1 - \frac{\min (mR, mG, mB)}{I (mR, mG, mB)} = 1 - \frac{m \cdot \min (R, G, B)}{m \cdot I (R, G, B)} = s (R, G, B),$$

and the Hue is also invariable

$$H (mR, mG, mB) = 63 \cdot \left( 1 + \frac{m \cdot (G' - R')}{m \cdot (G' + R')} \right) = H (R, G, B),$$

it does not depend on the Intensity.

Mixing of the colour $X$ with white colour by an addition of constant value $a \geq 0$ to the colour components, causes increase of Intensity value

$$I (R+a, G+a, B+a) = \left[ \frac{(R+a)^2 + (G+a)^2 + (B+a)^2}{3} \right]^{1/2} \geq \left[ \frac{R^2 + G^2 + B^2}{3} \right]^{1/2} = I (R, G, B).$$

According to table 1, the yellow triangles $YW$ and $YG$, forming the yellow rhombus $YGWR$, are having the minimal value of Blue component. If the vector $(a, a, a)$ is added to any colour from these triangles, the Saturation value should decrease. Therefore, following inequality should be fulfilled

$$s (R+a, G+a, B+a) \leq s (R, G, B) \Rightarrow 1 - \frac{\min (R+a, G+a, B+a)}{I (R+a, G+a, B+a)} \leq 1 - \frac{\min (R, G, B)}{I (R+a, G+a, B+a)} \Rightarrow$$

$$\Rightarrow \frac{\min (R, G, B) + a}{I (R+a, G+a, B+a)} \geq \frac{\min (R, G, B)}{I (R+a, G+a, B+a)} \Rightarrow \frac{B+a}{I (R+a, G+a, B+a)} \geq \frac{B}{I (R, G, B)}.$$

Introducing equation (4) to equation (20) the inequality takes the form

$$\frac{(B+a)^2}{(R+a)^2 + (G+a)^2 + (B+a)^2} \geq \frac{B^2}{R^2 + G^2 + B^2} \Rightarrow \frac{(R+a)^2 + (G+a)^2 + (B+a)^2}{(B+a)^2} \leq \frac{R^2 + G^2 + B^2}{B^2} \Rightarrow$$

$$\Rightarrow (R+a)^2 + (G+a)^2 + 1 \leq \frac{R^2 + G^2 + B^2}{B^2} \Rightarrow \frac{(R+a)^2 + (G+a)^2}{(B+a)^2} \leq \frac{R^2 + G^2}{B^2} \Rightarrow$$

$$\Rightarrow \left[ (R+a)^2 + (G+a)^2 \right] \cdot B^2 \leq \left( R^2 + G^2 \right) \cdot (B+a)^2,$$

which is satisfied in the yellow rhombus

$$2RB (B-R) + 2GB (B-G) + a (B^2 - R^2) + a (B^2 - G^2) \leq 0,$$

because obtained inequality (equation (22)) is true. All values in the parenthesis, due to the minimal value of Blue component, remain negative. It means that mixing of $X$ with white colour by addition of
constant value causes decrease in relative Saturation $s$. At the same time, the Hue value remains constant

$$H(R+a, G+a, B+a) = 63 \cdot \left(1 + \frac{(G-a-B)+R-a-B}{(G+a-B)+R+a-B}ight) = 63 \cdot \left(1 + \frac{(G-B)-(R-B)}{(G-B)+(R-B)}\right) = H(R, G, B). \quad (23)$$

Mixing of the $X$ colour with white one by an addition of vector $(a, b, c)$ causes an increase in the Intensity value, because at least one of $a$, $b$ or $c$ value is higher than zero

$$I \left[ \frac{R+w(1-R)}{a \geq 0}, \frac{G+w(1-G)}{b \geq 0}, \frac{B+w(1-B)}{c \geq 0} \right] = \left[ \frac{(R+a)^2+(G+b)^2+(B+c)^2}{3} \right]^{1/2} > \left( \frac{R^2+G^2+B^2}{3} \right)^{1/2} = I(R, G, B). \quad (24)$$

In such situation the Saturation should decrease and following inequality should be fulfilled

$$S[(1-w) \cdot X + w \cdot W] < S(X). \quad (25)$$

This relation can be proved after re-writing equation (15) in an equivalent form of following equation

$$(1-w) \cdot X + \frac{w}{(1-w)} \cdot W = Z. \quad (26)$$

Inserting equation (26) into equation (25), term $(1-w)$ can be withdrawn and quotient must be positive $w \cdot (1-w)^{-1} > 0$. It is fulfilled because $0 < w < 1$ ($w = 0$ represents pure colour, while $w = 1$ represents addition of infinite amount of white colour). Presented above prove of Saturation decreasing, when the colours are mixed, can be utilized for the confirmation of Hue invariability. The Hue value remains invariant, due to

$$H[(1-w) \cdot R + w, (1-w) \cdot G + w, (1-w) \cdot B + w] = 63 \cdot \left(1 + \frac{[(1-w) \cdot (G-B)+w-u]-[(1-w) \cdot (R-B)+w-u]}{[(1-w) \cdot (G-B)+w-u]+[(1-w) \cdot (R-B)+w-u]}\right)$$

$$= 63 \cdot \left(1 + \frac{(G-B)-(R-B)}{(G-B)+(R-B)}\right) = H(R, G, B). \quad (27)$$

7. Summary

The light reflected from TLC particles is closely connected with their temperature. This feature is utilized in the PIT method. Image analysis requires transformation of $RGB$ colour space to $HSI$ one. Advantage of presented in this paper transformation is coming from the possibility of storing the colour components as 8-bit integer numbers.

In the paper the non-linear relation defining Hue, presented in [15-17] was derived and it was shown that it has common origin with the linear functions presented in [8-10]. It was proved that derived formulas fulfilled the criterion of Hue invariability in the plane containing Intensity axis and criterion of Hue independence on the Intensity and Saturation. These requirements should be fulfilled by all colour space transformations applied in the PIT method. Derivation of the formulas and described criteria construct the theoretical approach to the experimental procedure with image analysis and conscious choice of computer tools. It supplements the knowledge on the PIT and digital image processing.

8. References

[1] Park H G, Dabiri D and Gharib M 2001 Digital particle image velocimetry/thermometry and application to the wake of heated circular cylinder Exp. Fluids 30 pp 327–338

[2] Kowalewski T A, Cybulski A and Rebow M Particle Image Velocimetry and Thermometry in Freezing Water 8th International Symposium on Flow Visualization (Sorrento, Italy, September 1-4, 1994)
[3] Fornalik E, Leiner W, Szmyd S J, Kowalewski T A and Ozoe H 2005 Visualization of the Flow Structure and Temperature Field in the Region of Mixed Convection in Mechanics of 21st Century (Springer Verlag)

[4] Fornalik E, Yamamoto Y, Chen W, Nakabe K and Suzuki K 1999 Visualization of heat transfer enhancement regions modified by the interaction of inclined impinging jets into crossflow, MG&V 8 pp 597–609

[5] Bednarz T, Fornalik E, Tagawa T, Ozoe H and Szmyd J S 2006 Convection of paramagnetic fluid in a cube heated and cooled from side walls and placed below a superconducting magnet: comparison between experiment and numerical computations Thermal Science and Engineering 14 pp 107-114

[6] Stasiek J, Jewartowski M and Kowalewski T A 2014 The Use of Liquid Crystal Thermography in Selected Technical and Medical Applications Journal of Crystallization Process and Technology 4 pp 46-59

[7] Dabiri D and Gharib M 1991 Digital particle image thermometry: The method and implementation, Exp. Fluids 11 pp 77–86

[8] Smith A R 1978 Color Gamut Transform Pairs SIGGRAPH ’78 Proc. of the 5th annual Conf. on Computer graphics and interactive techniques (New York) vol 12 (New York: ACM) pp 12–19

[9] Foley J D, van Dam A, Feiner S K and Hughes J F 1996 Computer Graphics: Principles and Practice in C, 2nd ed. (Addison–Wesley)

[10] http://www.oracle.com/technetwork/java/javase/downloads/index.html

[11] Russ J C 2002 The Image Processing Handbook, 4th ed. (Boca Raton, London, New York, Washington D.C.: CRC Press LLC)

[12] Bunting F 1998 The ColorShop Color Primer (Light Source Computer Images, Inc. An X-Rite Company)

[13] Gonzalez R C and Woods R E 2002 Digital Image Processing, 2nd ed. (Upper Saddle River, New Jersey: Prentice Hall)

[14] Hay J L and Hollingsworth T H 1996 A Comparison of Trichromic Systems for Use in the Calibration of Polymer-Dispersed Thermochromic Liquid Crystals Exp. Therm. Fluid Sci. 12 pp 1–12

[15] Kowalewski T A 2007 Thermochronic Liquid Crystals, in Handbook of Experimental Fluid Mechanics ed C Tropea, A Yarin and J F Foss (Berlin, Heidelberg: Springer–Verlag) chapter B7.1 pp 487-500

[16] Hiller W J, Koch St, Kowalewski T A and Stella F 1993 Onset of natural convection in a cube Int. J. Heat Mass Tran. 36 pp 3251-3263

[17] Kowalewski T A 1999 Particle Image Velocimetry and Thermometry Using Liquid Crystals FLUVISU 99, 8me colloque nationale de visualisation et de traitement d'images en mecanique des fluids (Toulouse, France, June 1-4 1999) ENSICA pp 33-48
http://fluid.ippt.pan.pl/papers/fluvis99_tkowale.pdf

Acknowledgement
The present work was supported by the Polish Ministry of Science (Grant AGH No. 11.11.210.198).